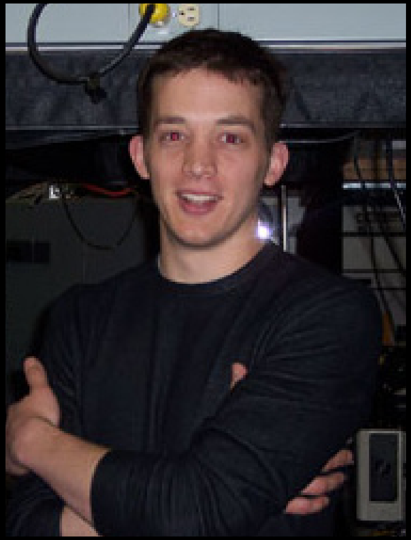
Pushing Materials Research towards a commercial impact

Universiti Teknologi Malaysia
Johor Bahru, Malaysia, 29 March 2012



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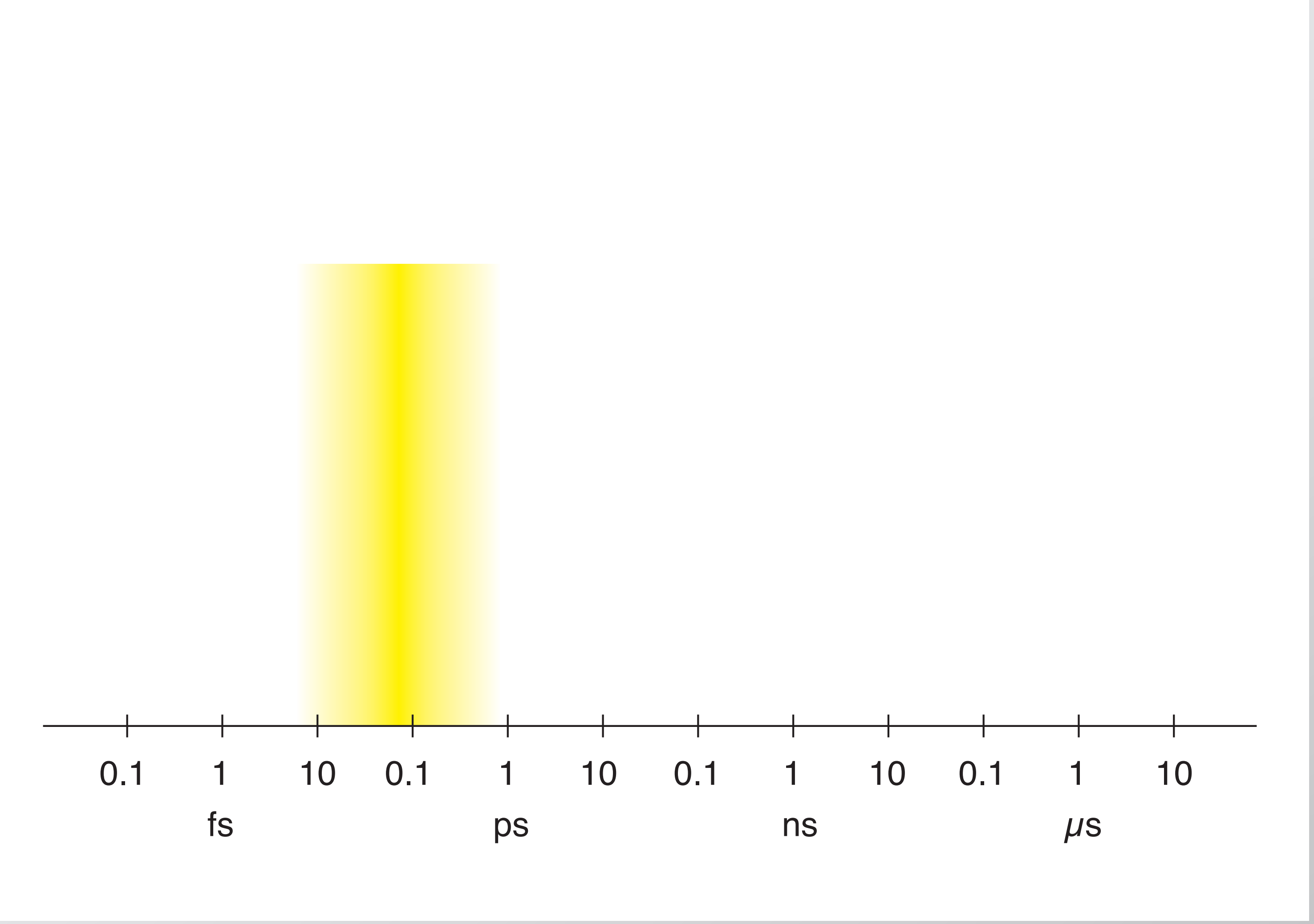
Introduction

why study materials with femtosecond pulses?

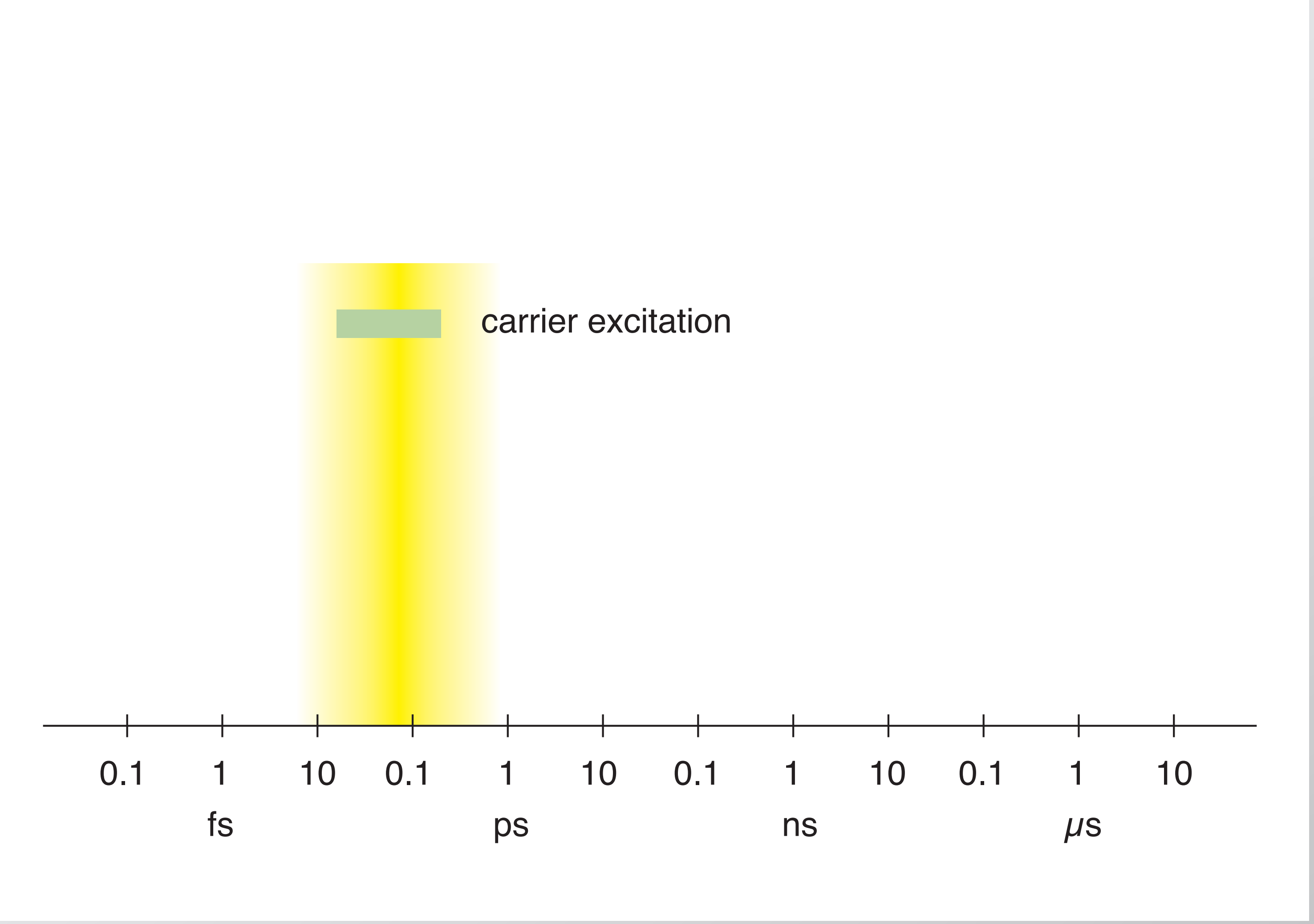
Introduction

relevant time scales



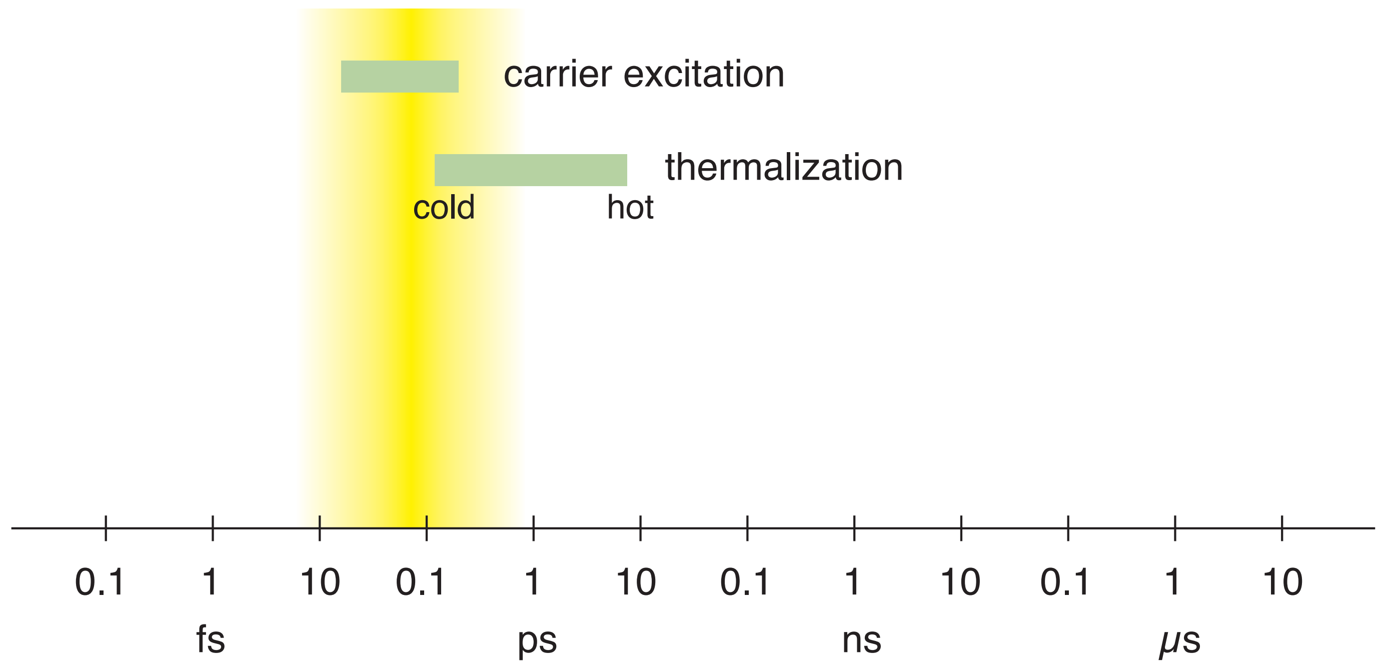
Introduction

relevant time scales



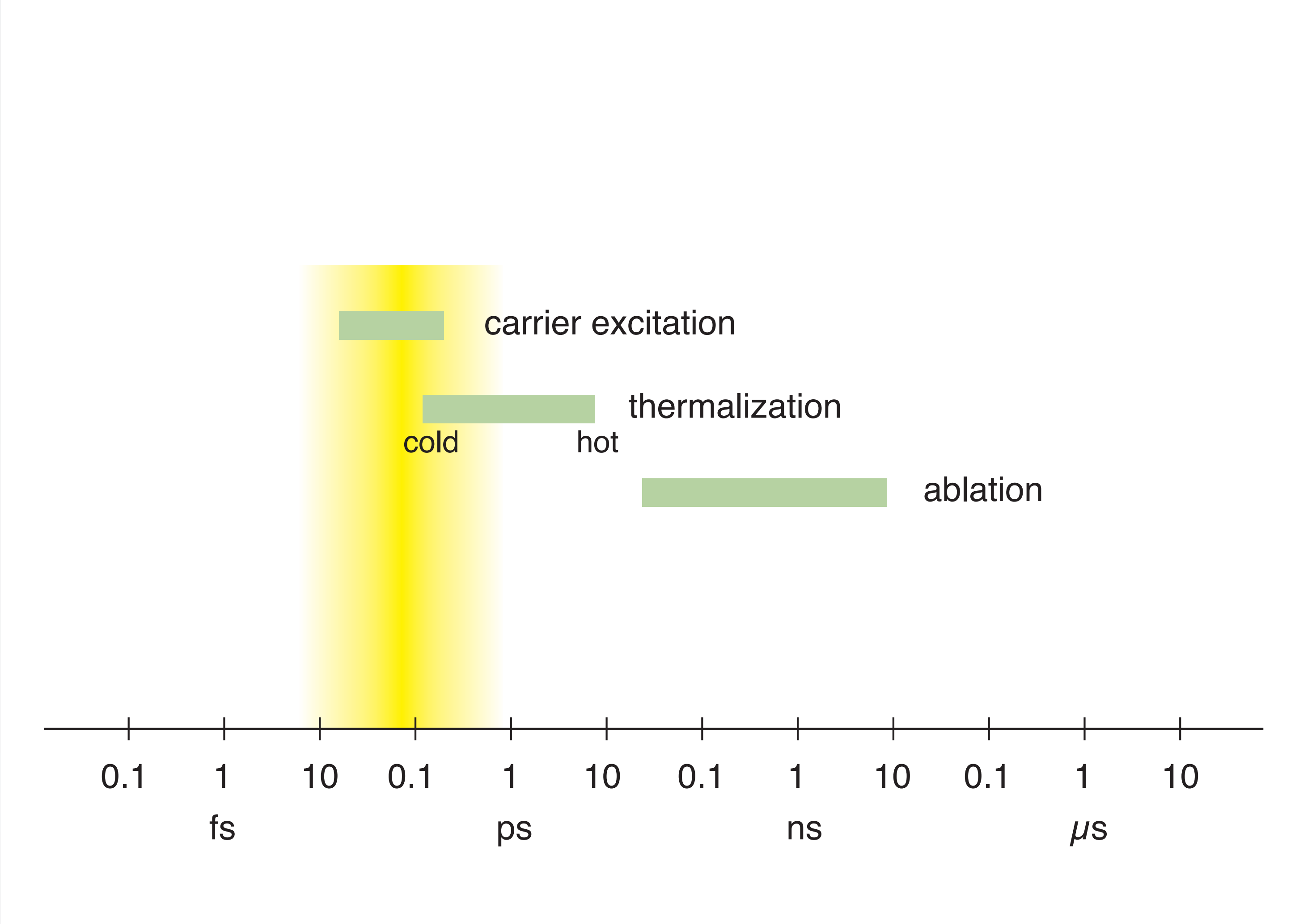
Introduction

relevant time scales



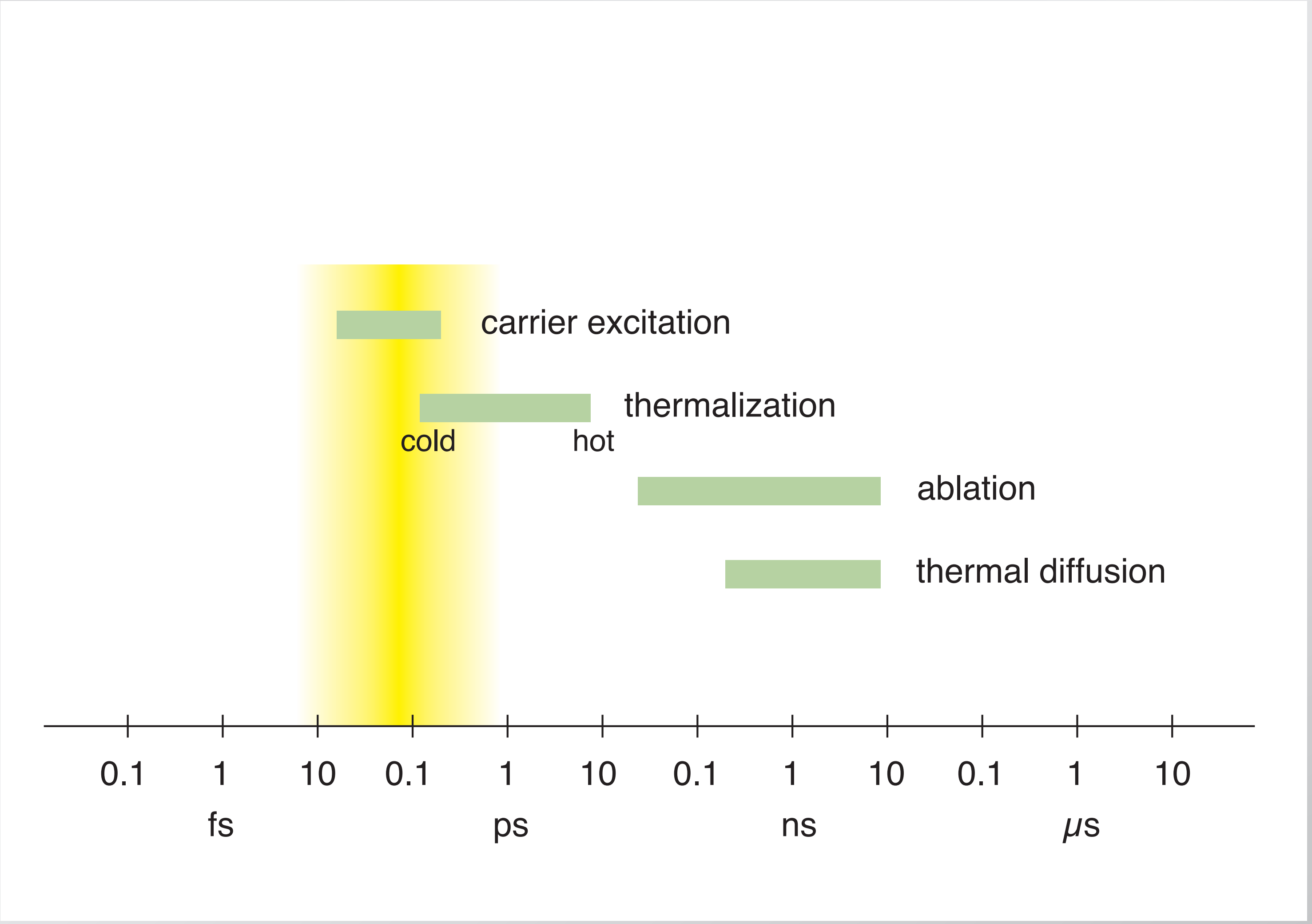
Introduction

relevant time scales



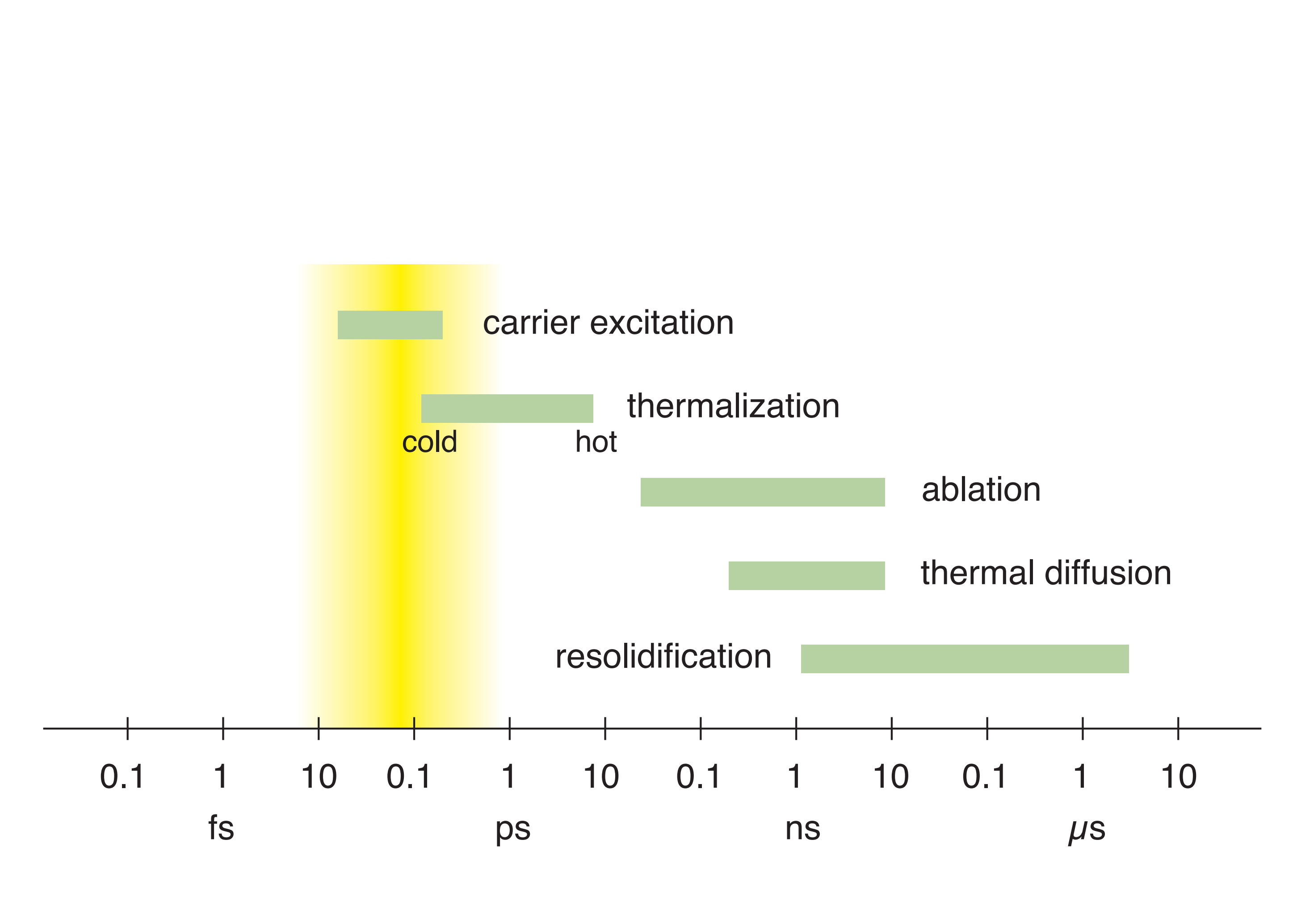
Introduction

relevant time scales



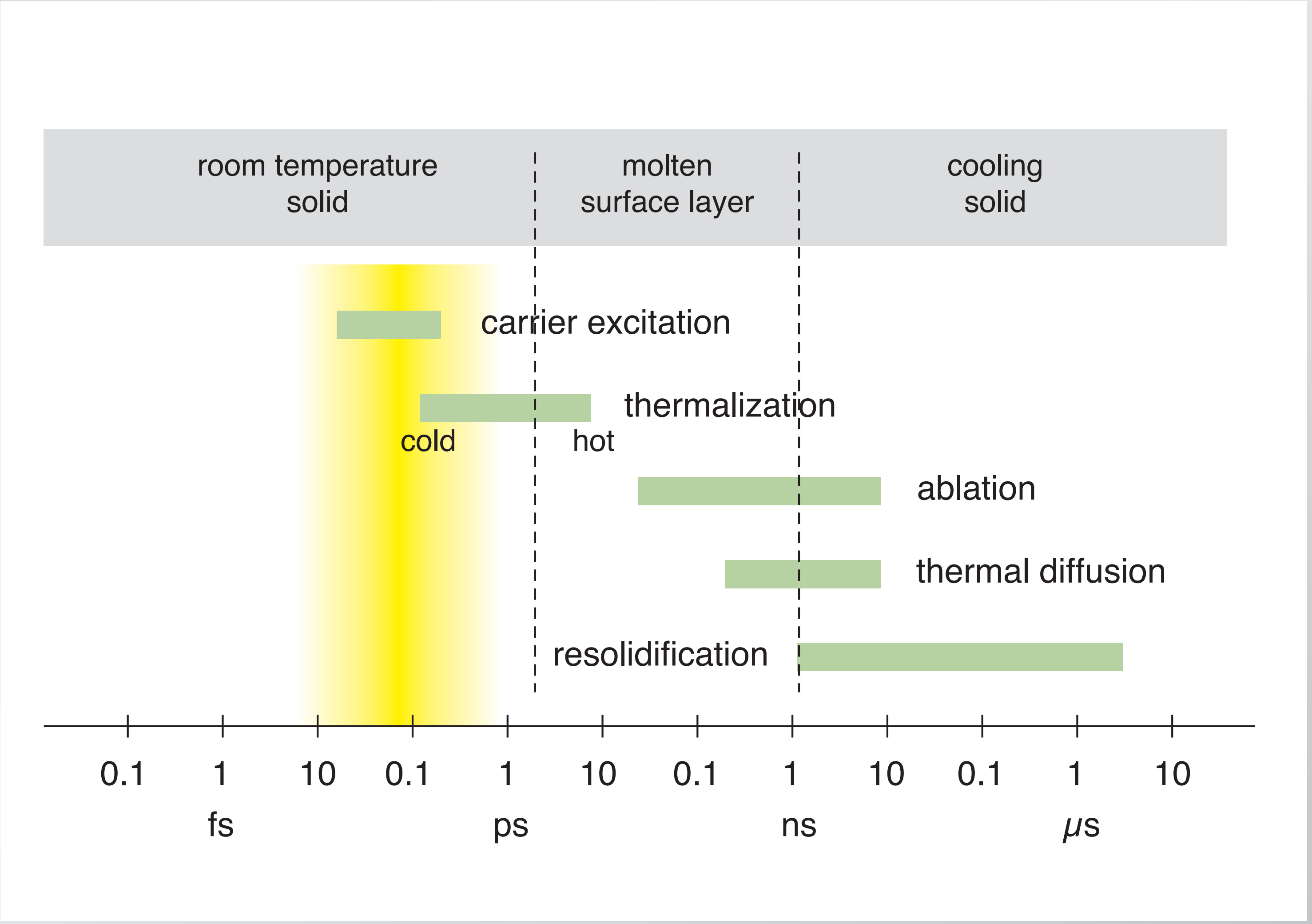
Introduction

relevant time scales



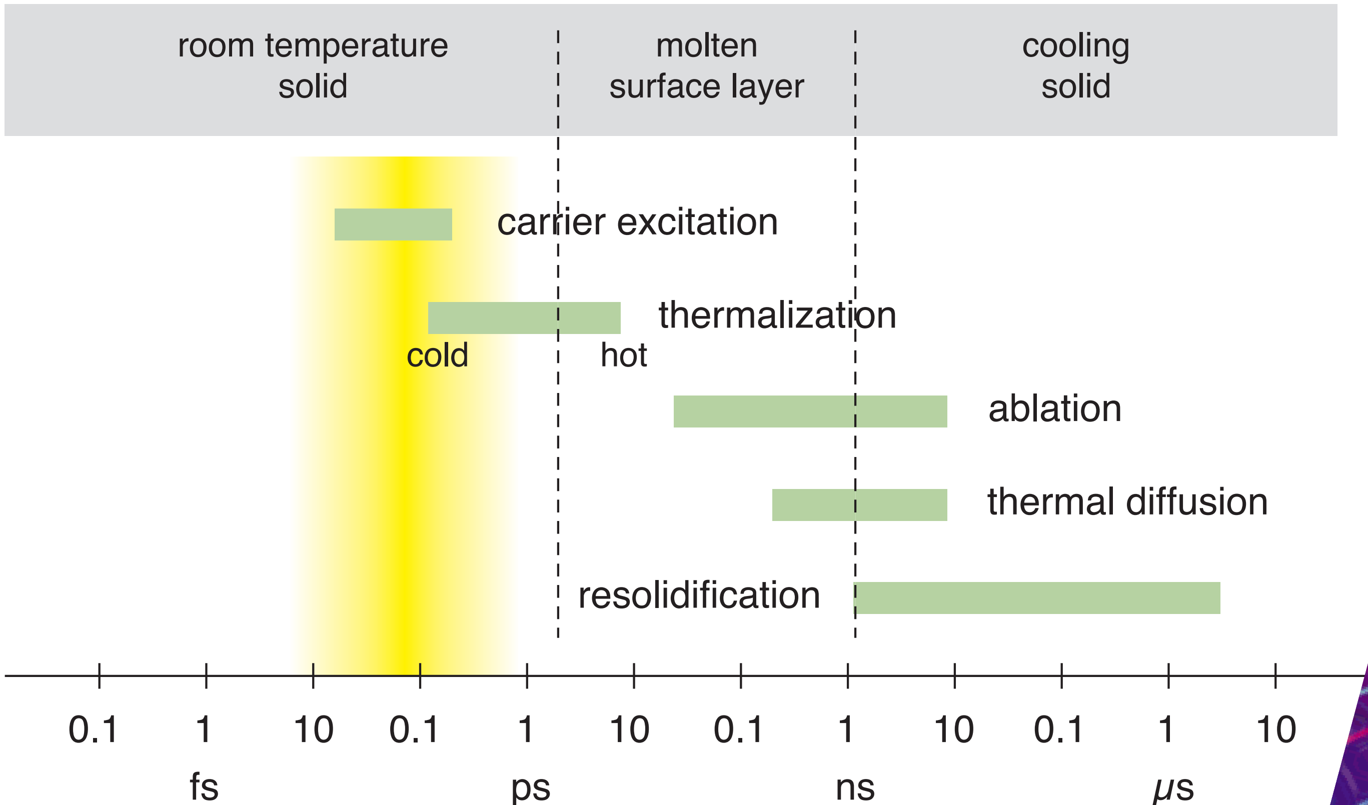
Nontransparent materials

relevant time scales



Nontransparent materials

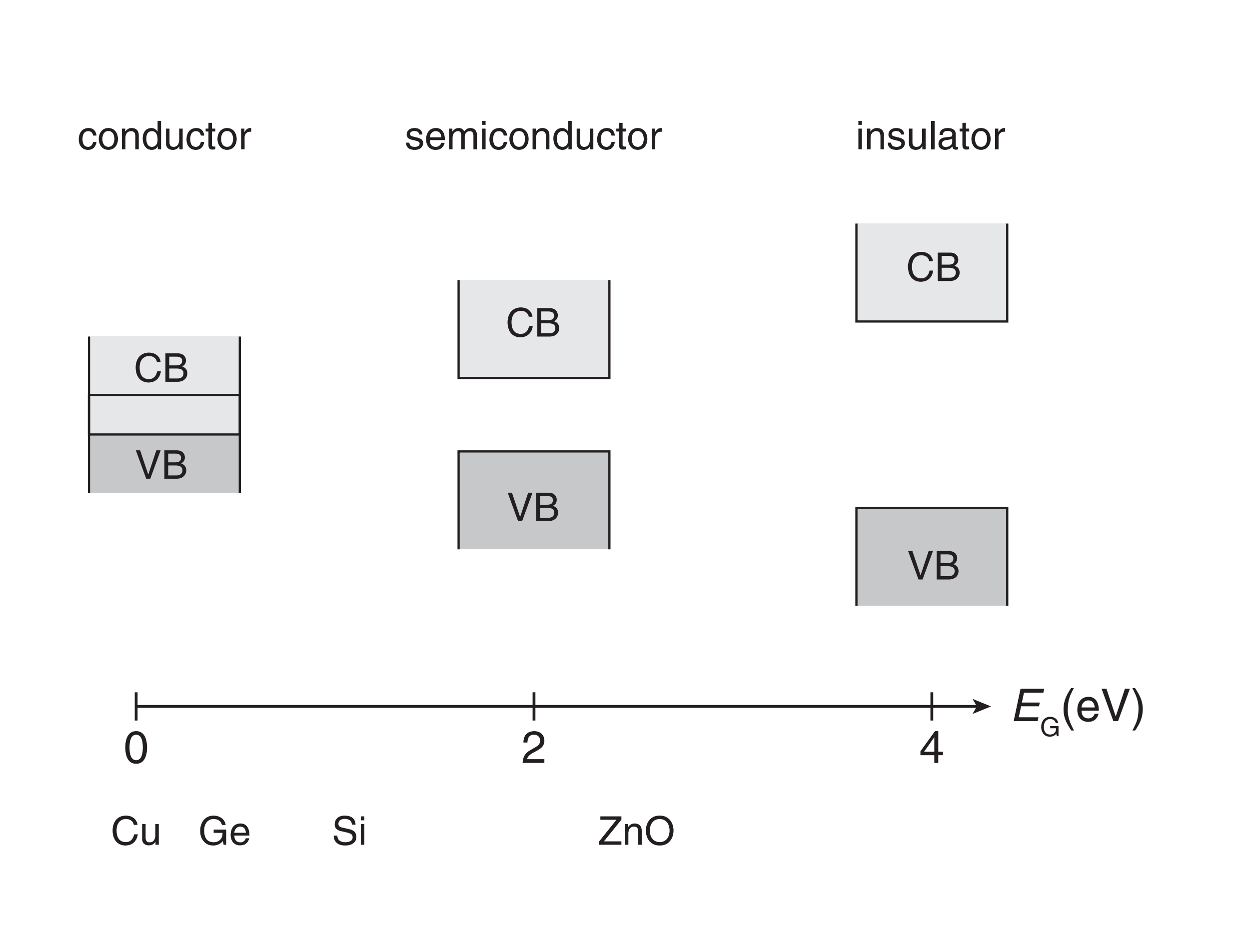
relevant time scales



Nature Materials **2**, 217 (2002)

Nontransparent materials

gap determines interaction

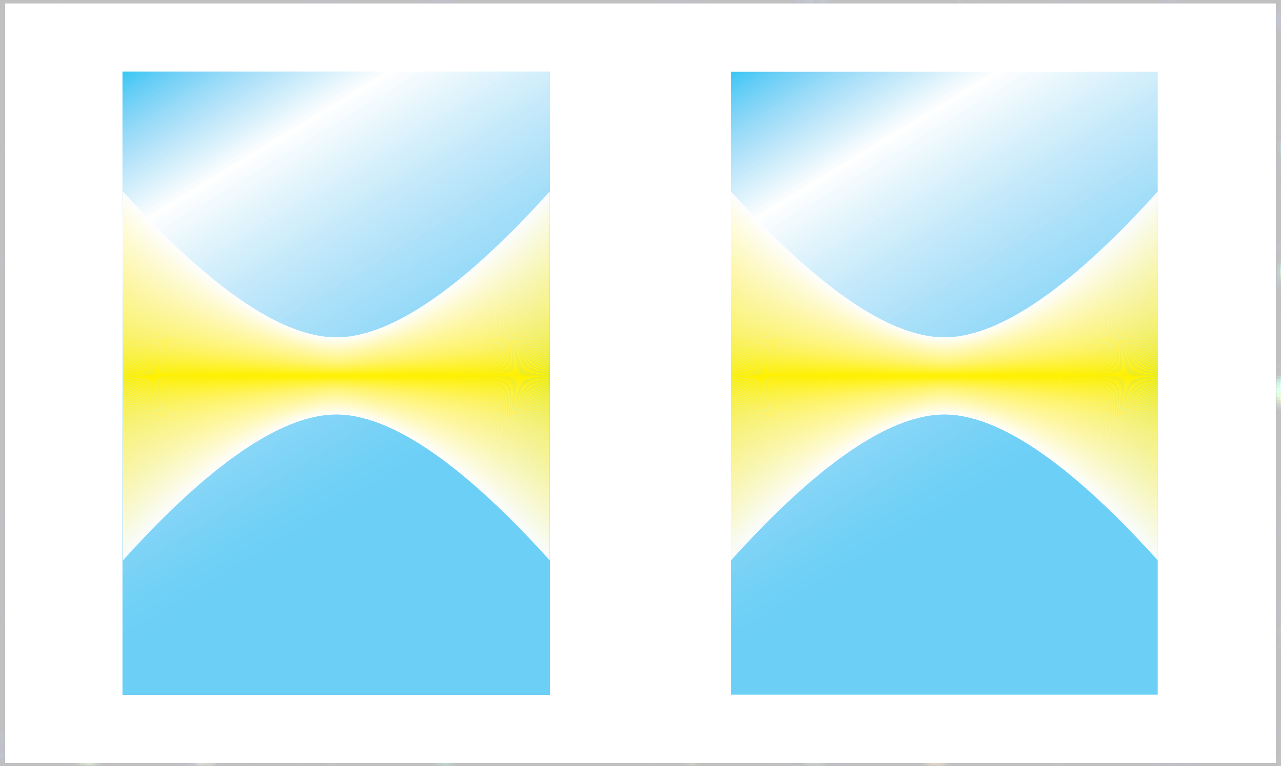


Introduction

photon energy < bandgap $\longrightarrow$ nonlinear interaction

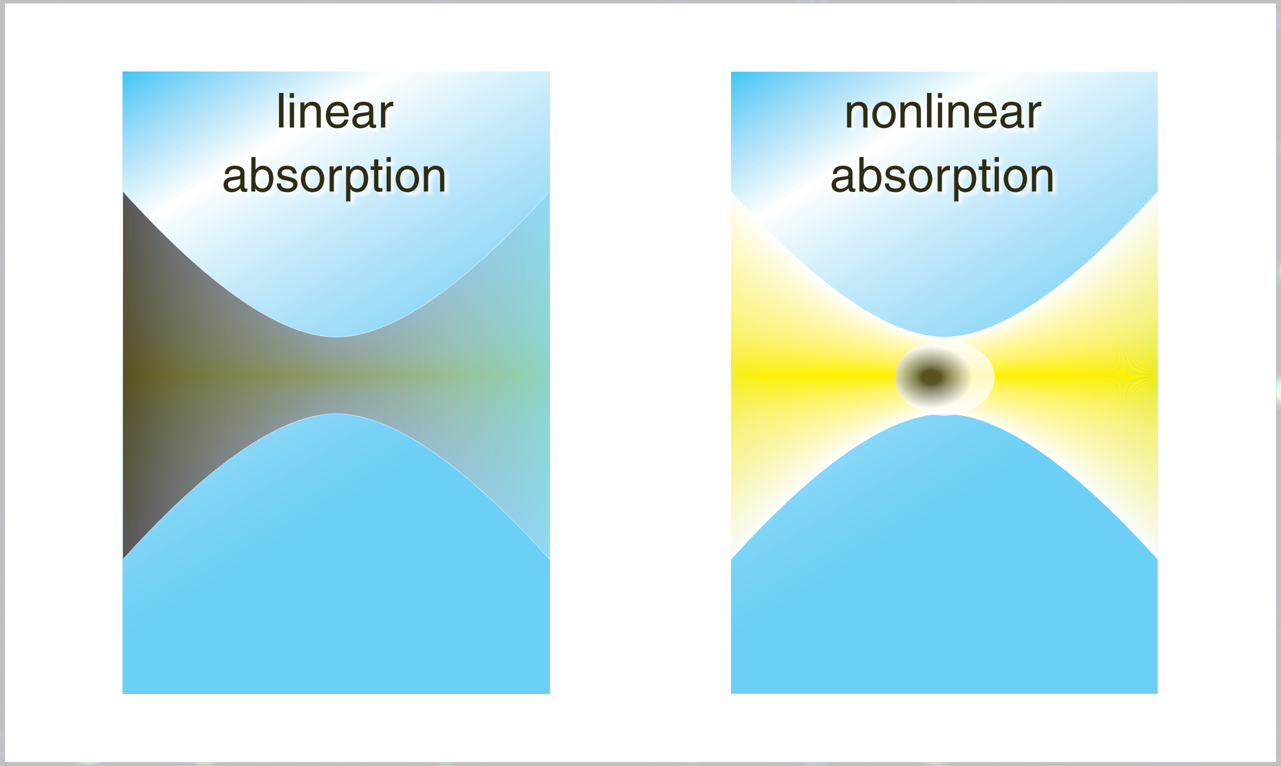
Introduction

nonlinear interaction provides bulk confinement



Introduction

nonlinear interaction provides bulk confinement

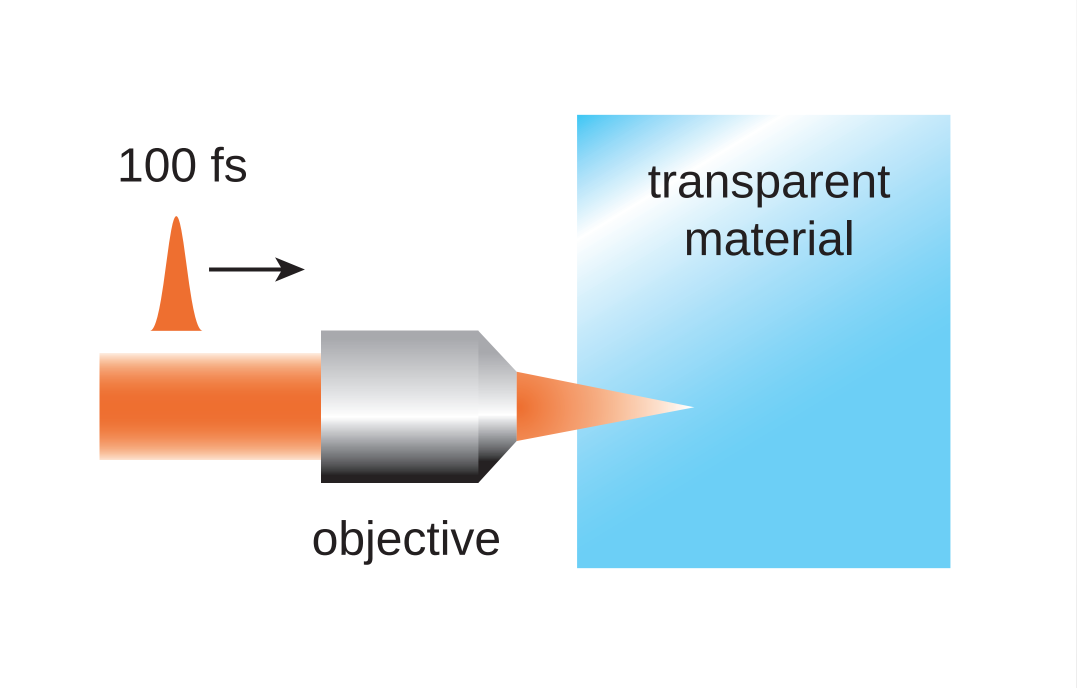


Outline

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

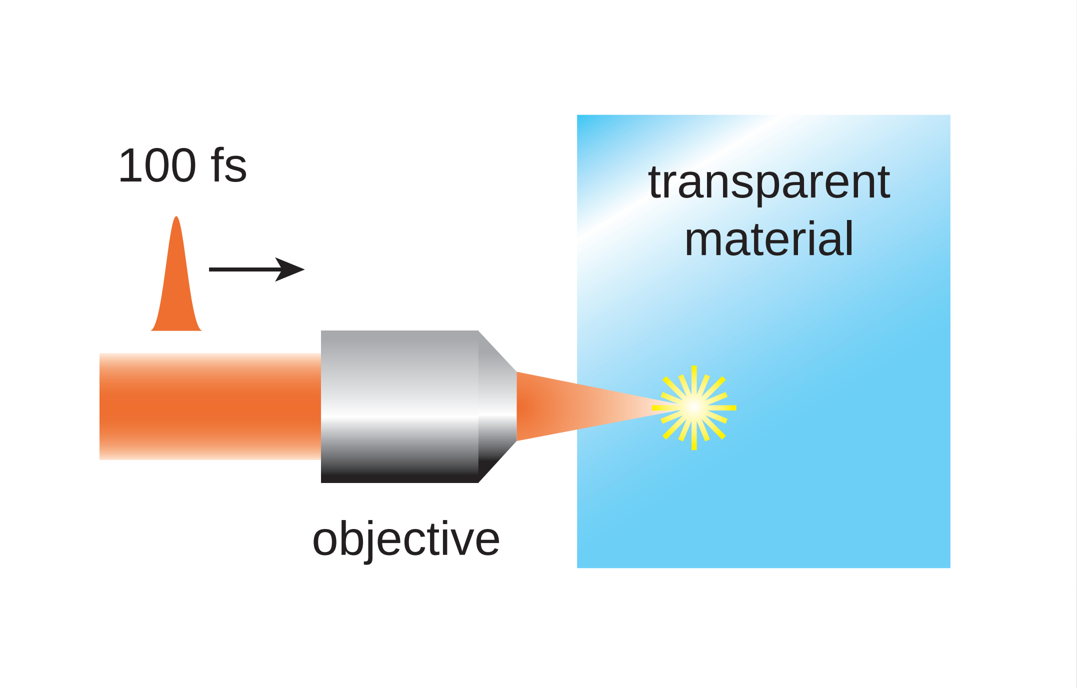
Transparent materials

high intensity at focus…



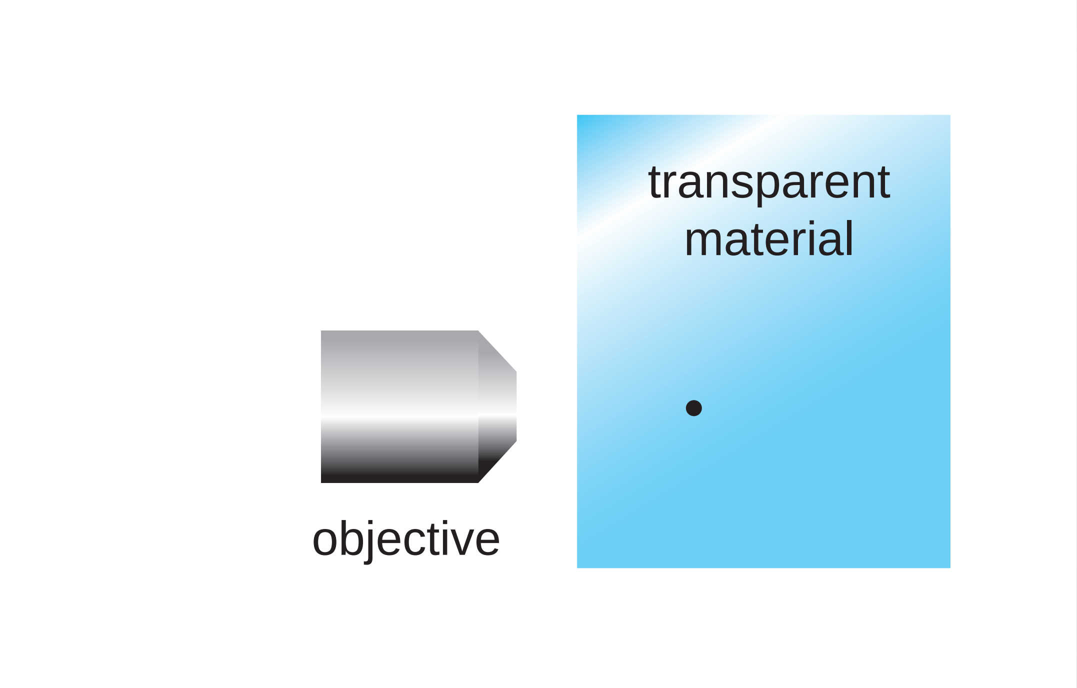
Transparent materials

…causes nonlinear ionization…

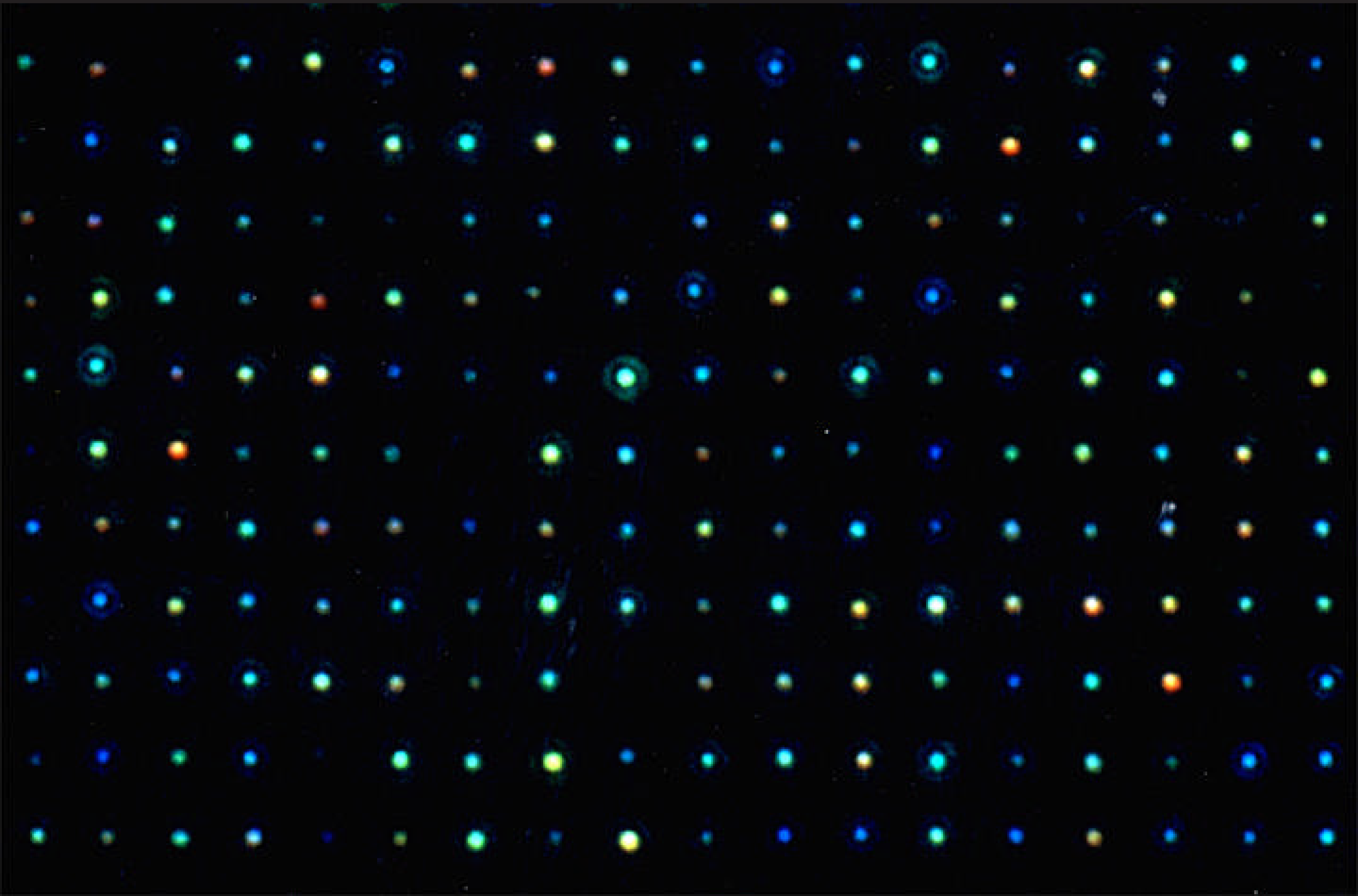


Transparent materials

and 'microexplosion' causes microscopic damage…



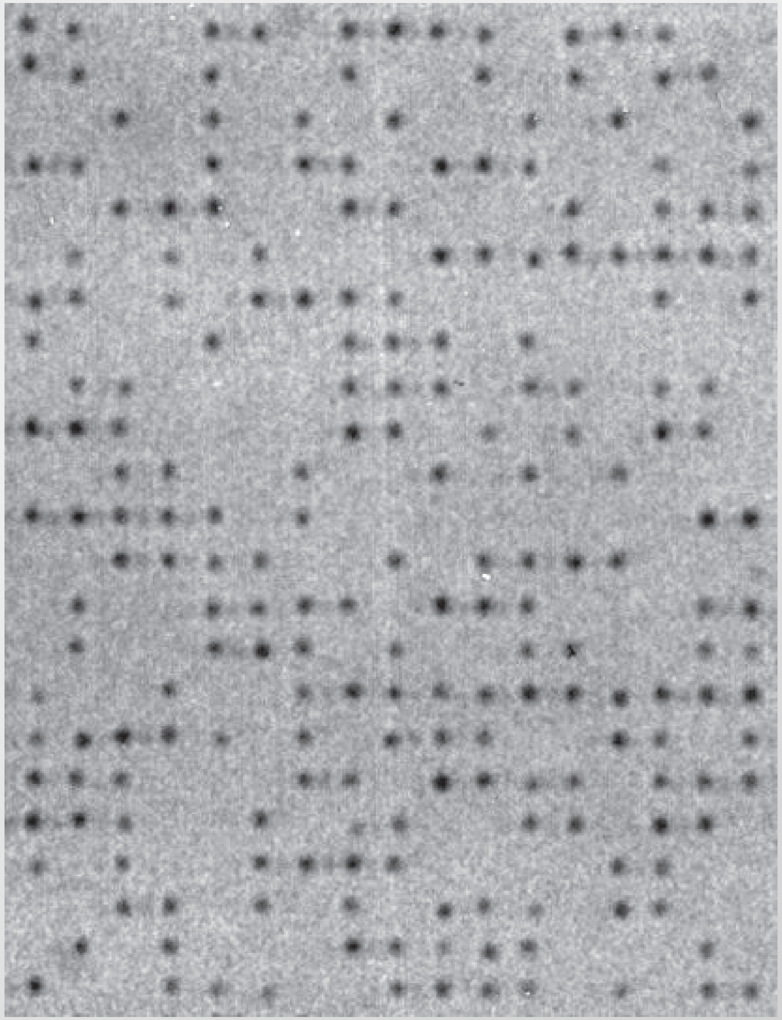
Transparent materials



Transparent materials

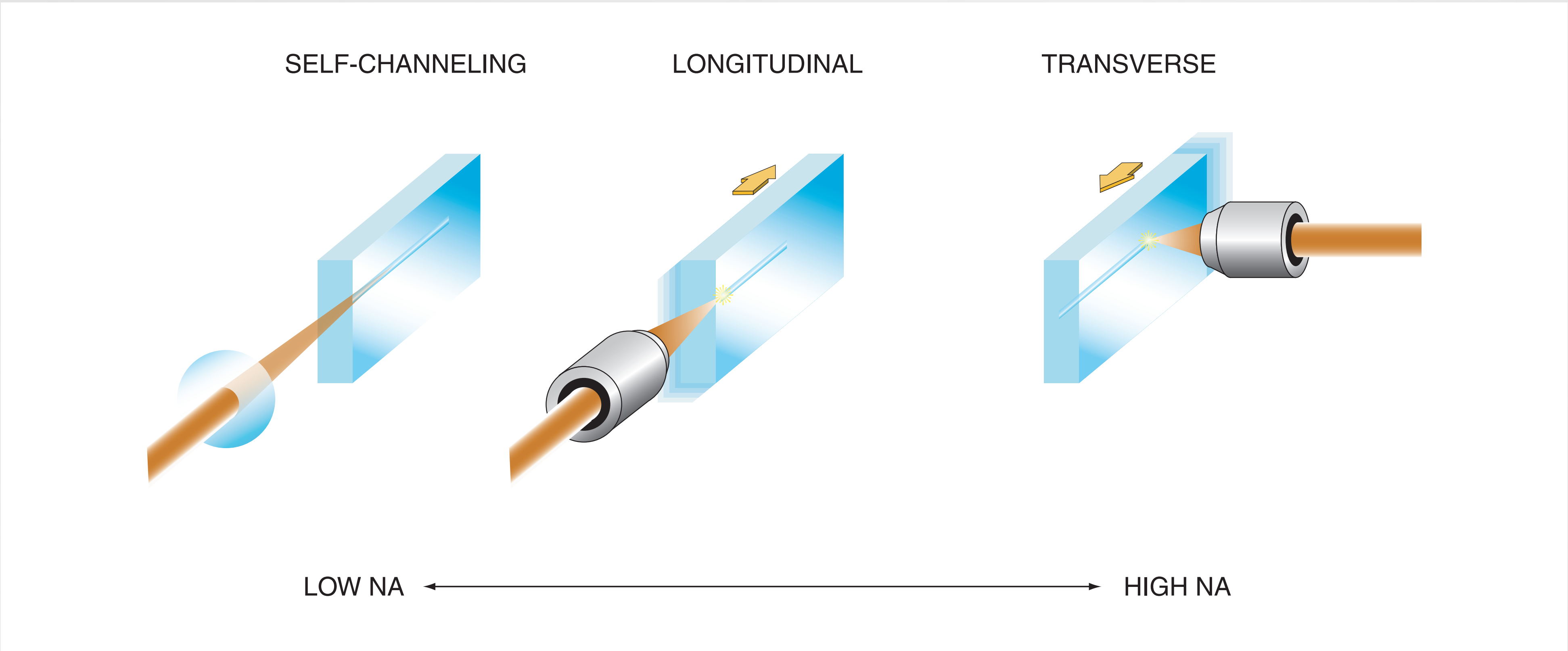
Some applications:

- data storage
- waveguides
- microfluidics



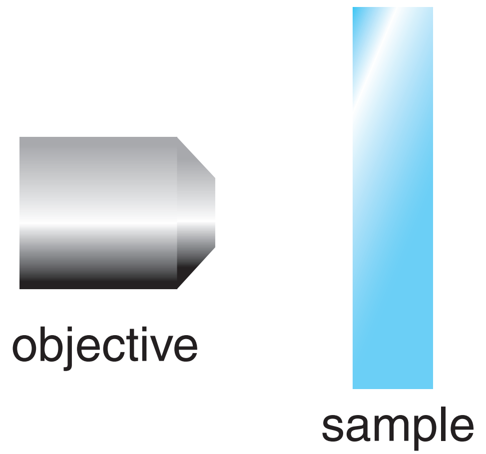
Transparent materials

waveguide micromachining geometries



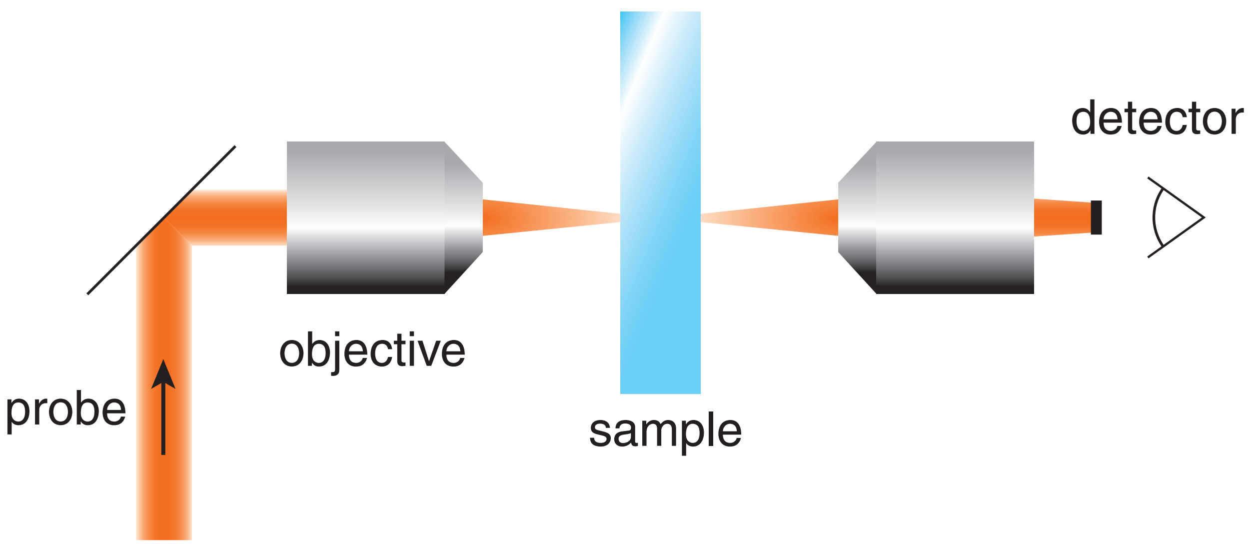
Transparent materials

Dark-field scattering



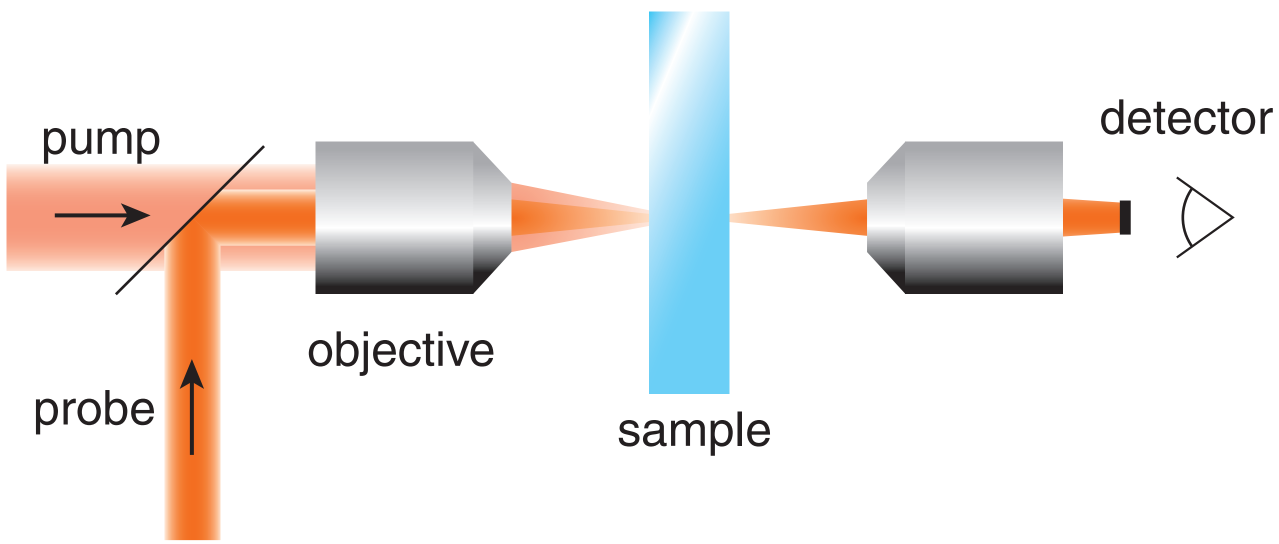
Transparent materials

block probe beam…



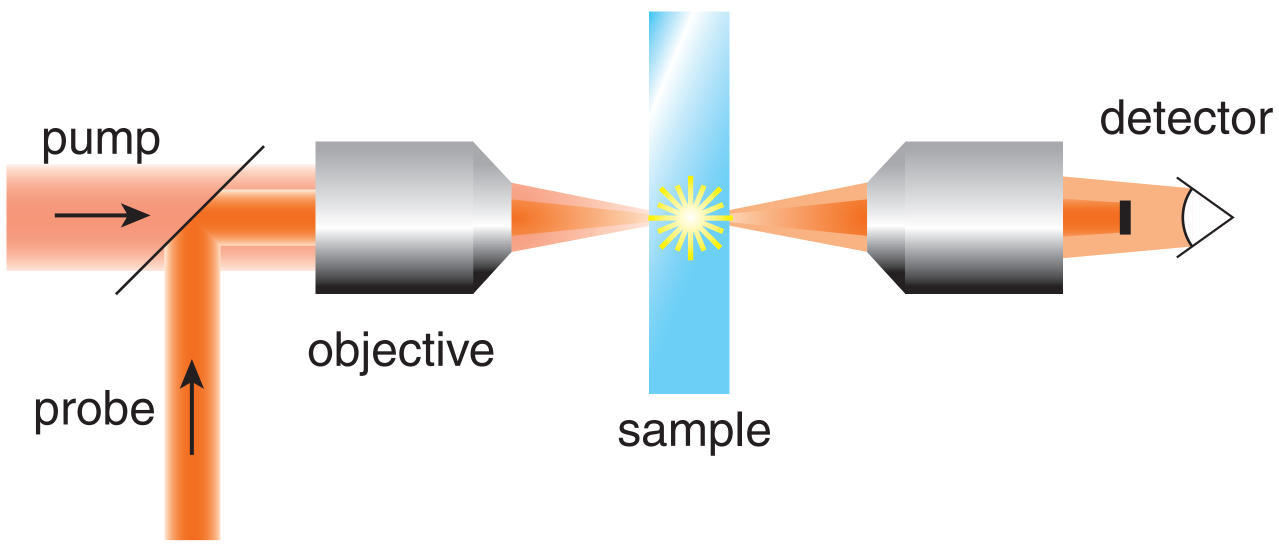
Transparent materials

… bring in pump beam…



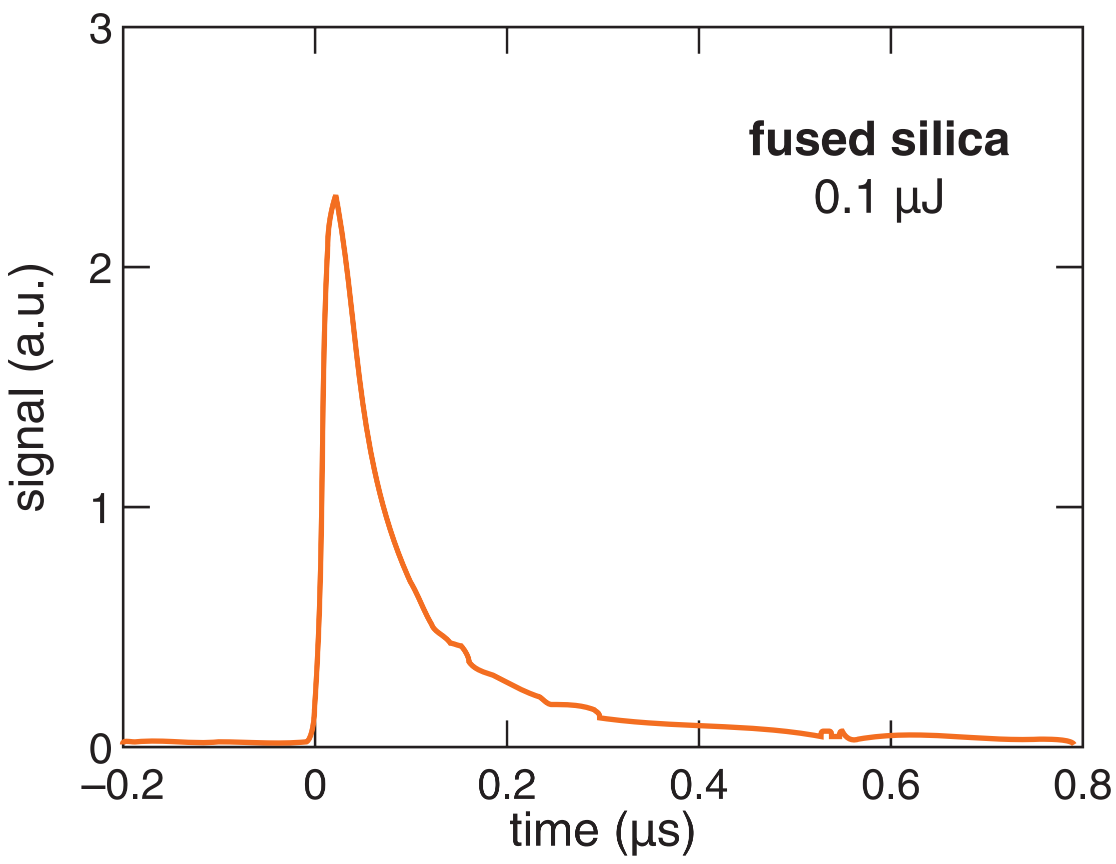
Transparent materials

… damage scatters probe beam



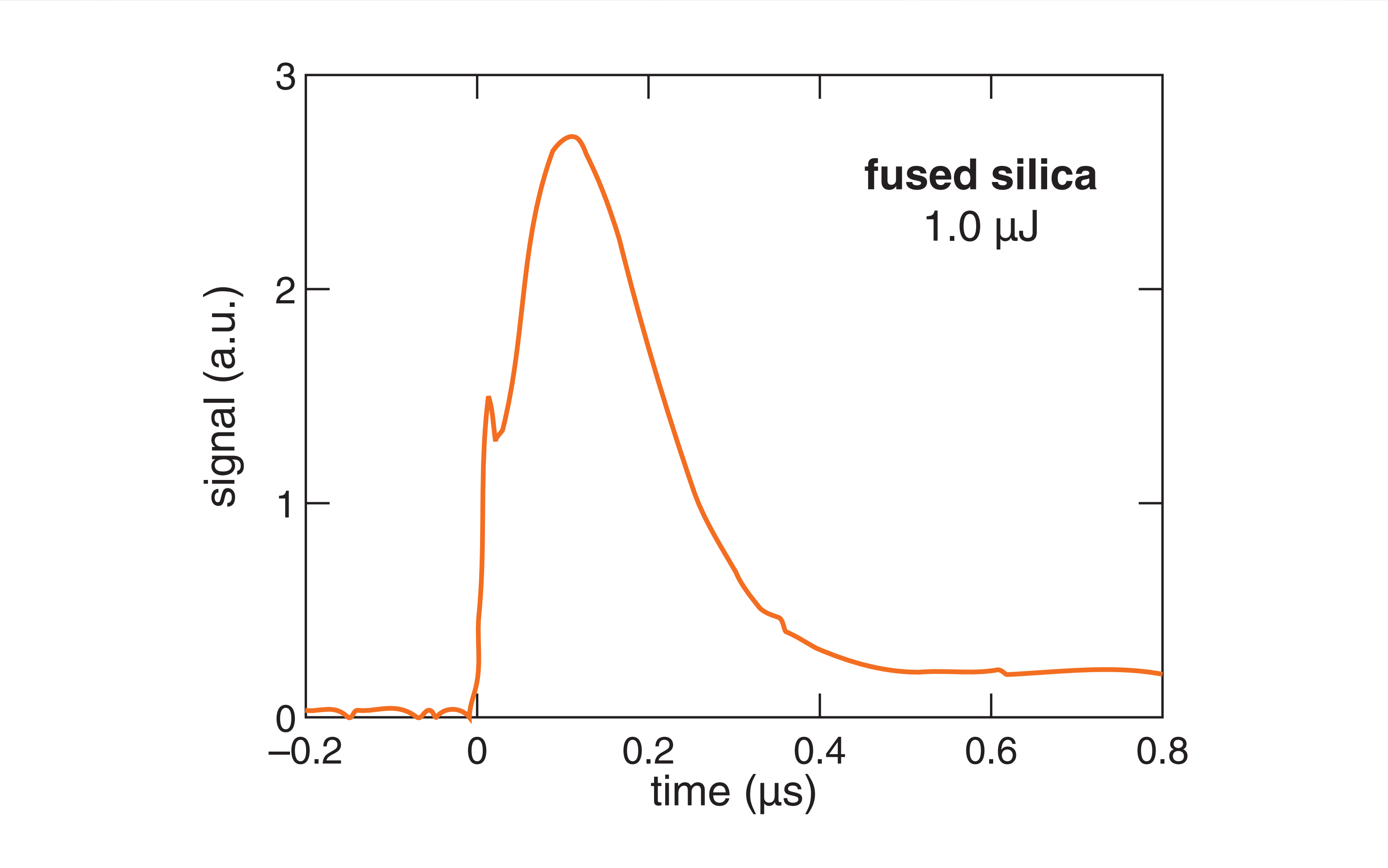
Transparent materials

scattered signal



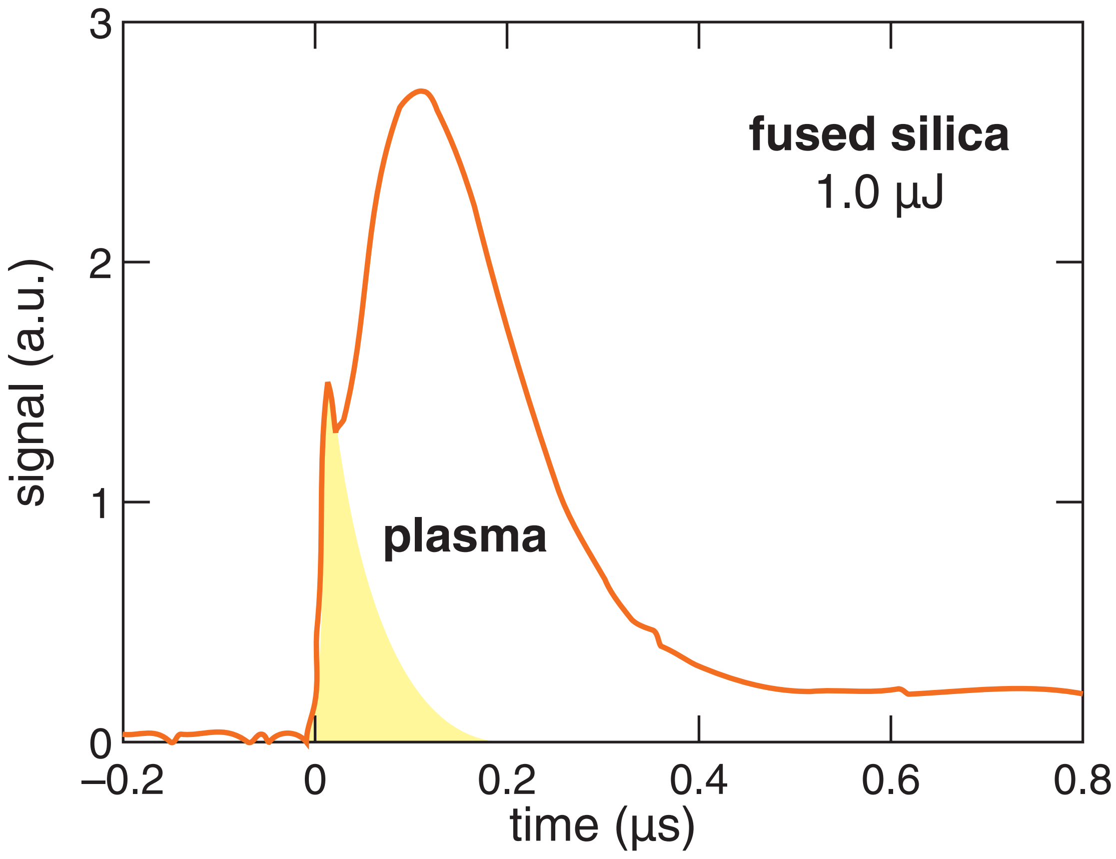
Transparent materials

scattered signal



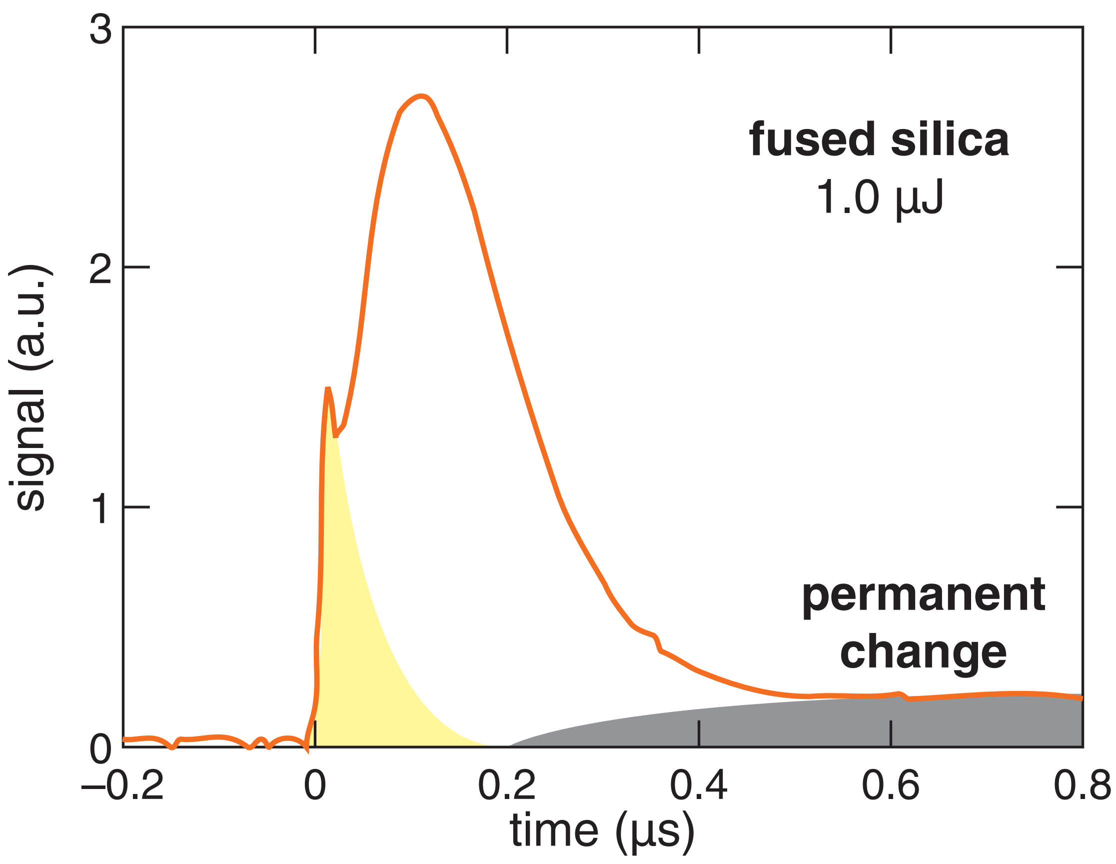
Transparent materials

scattered signal



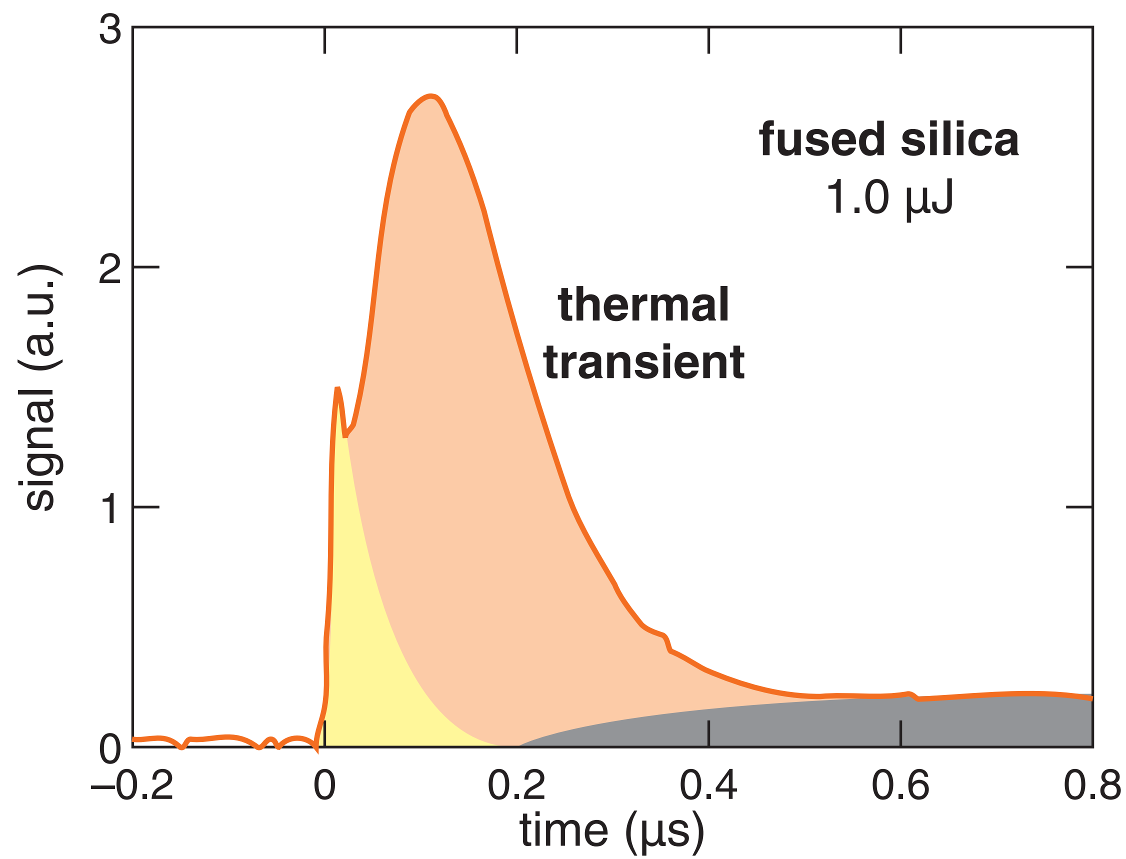
Transparent materials

scattered signal



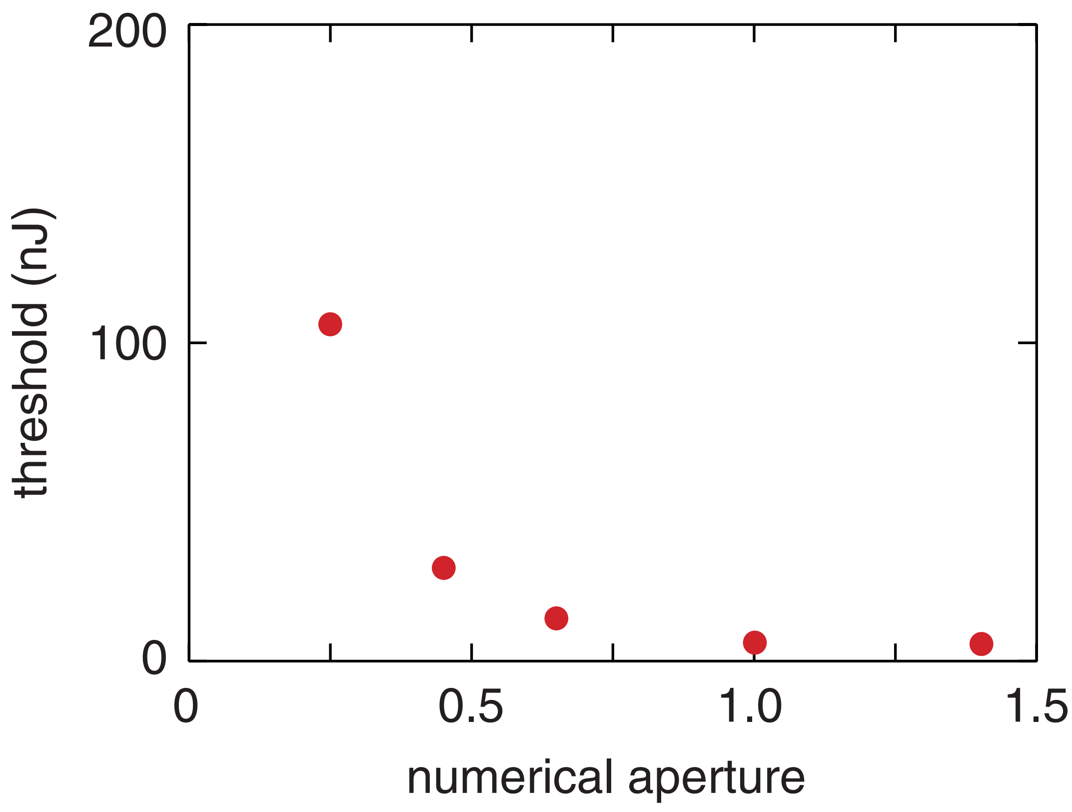
Transparent materials

scattered signal



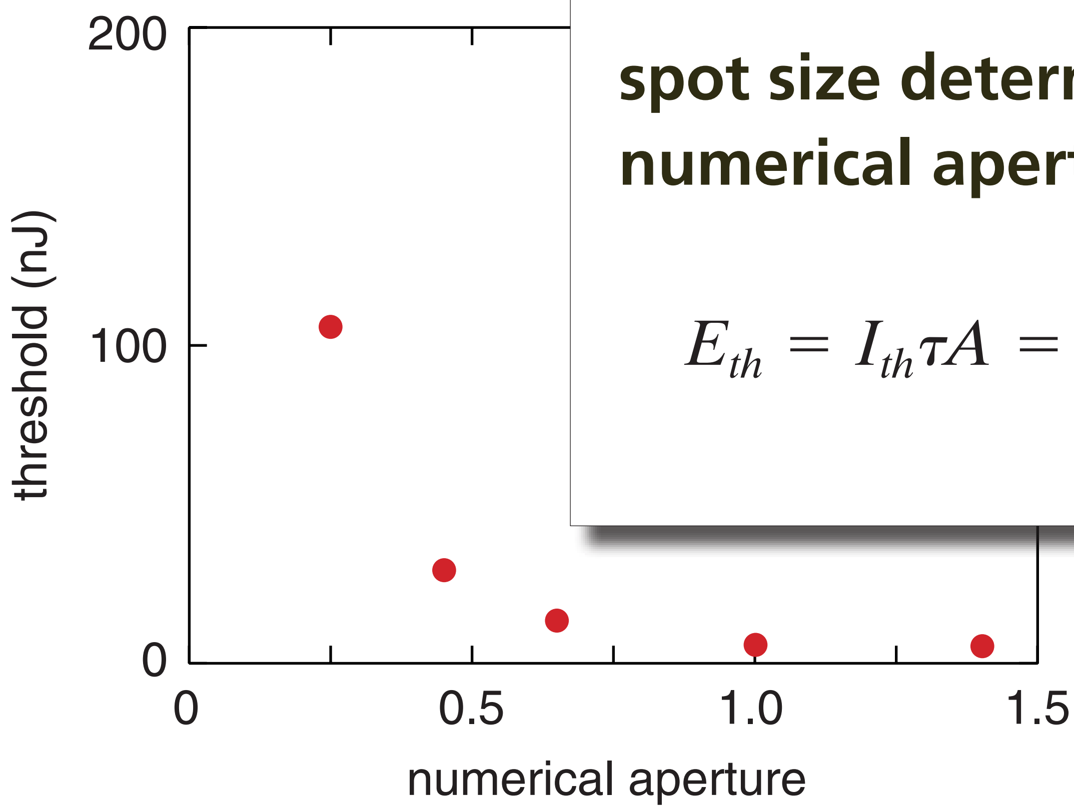
Transparent materials

vary numerical aperture



Transparent materials

vary numeric



intensity threshold:

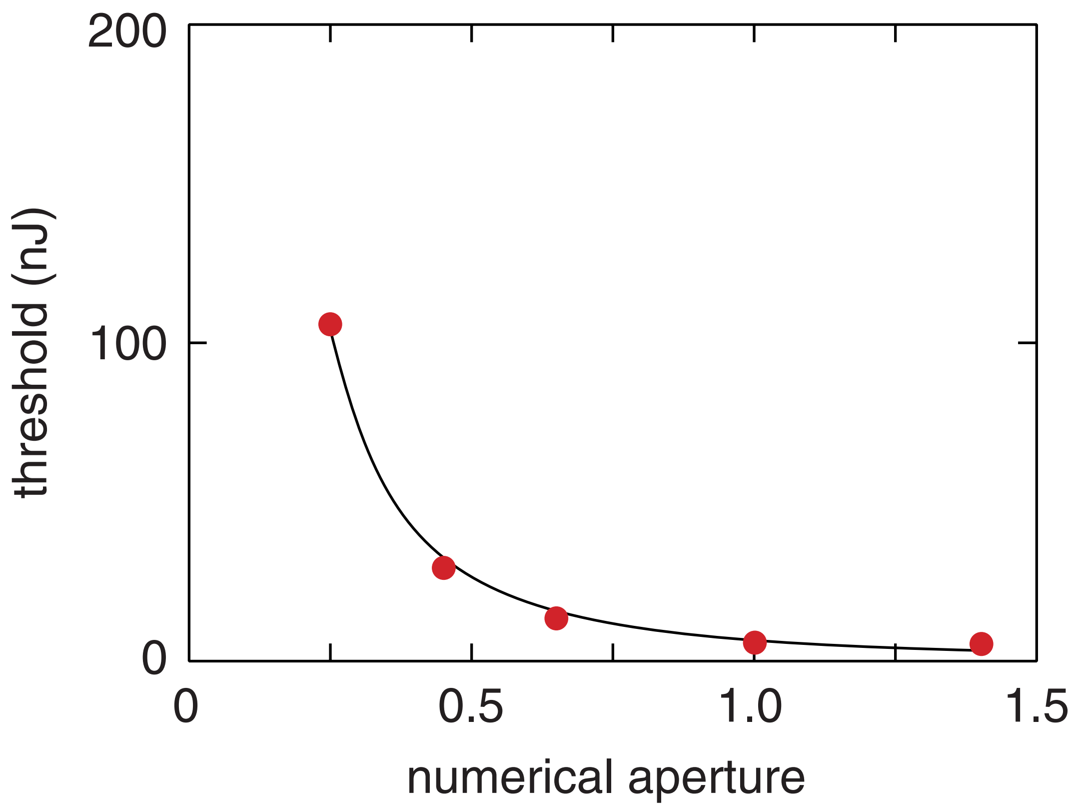
$$E_{th} = I_{th}\tau A$$

spot size determined by numerical aperture:

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

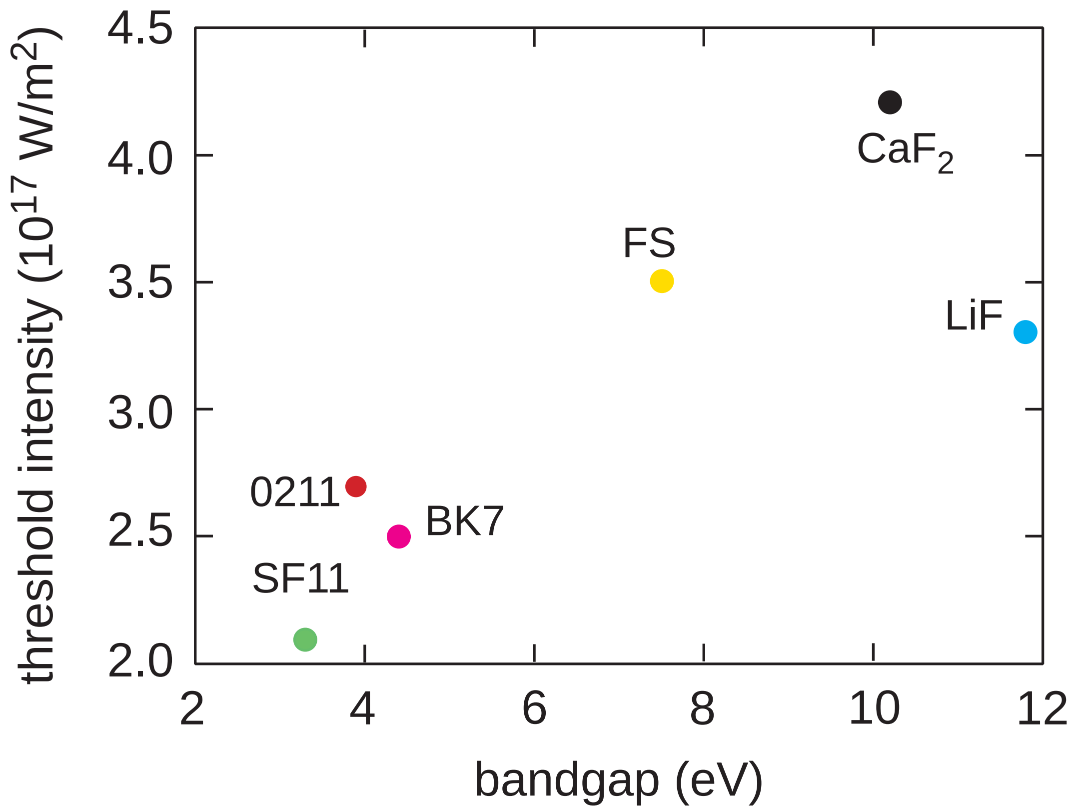
Transparent materials

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



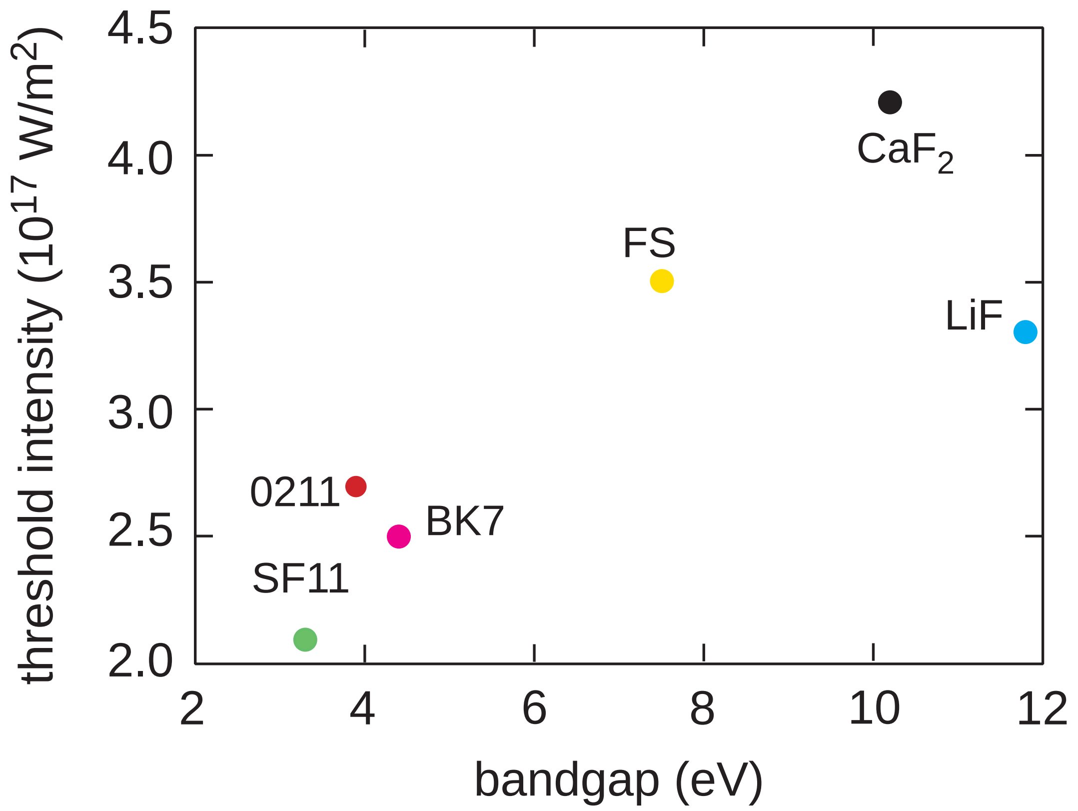
Transparent materials

vary material…



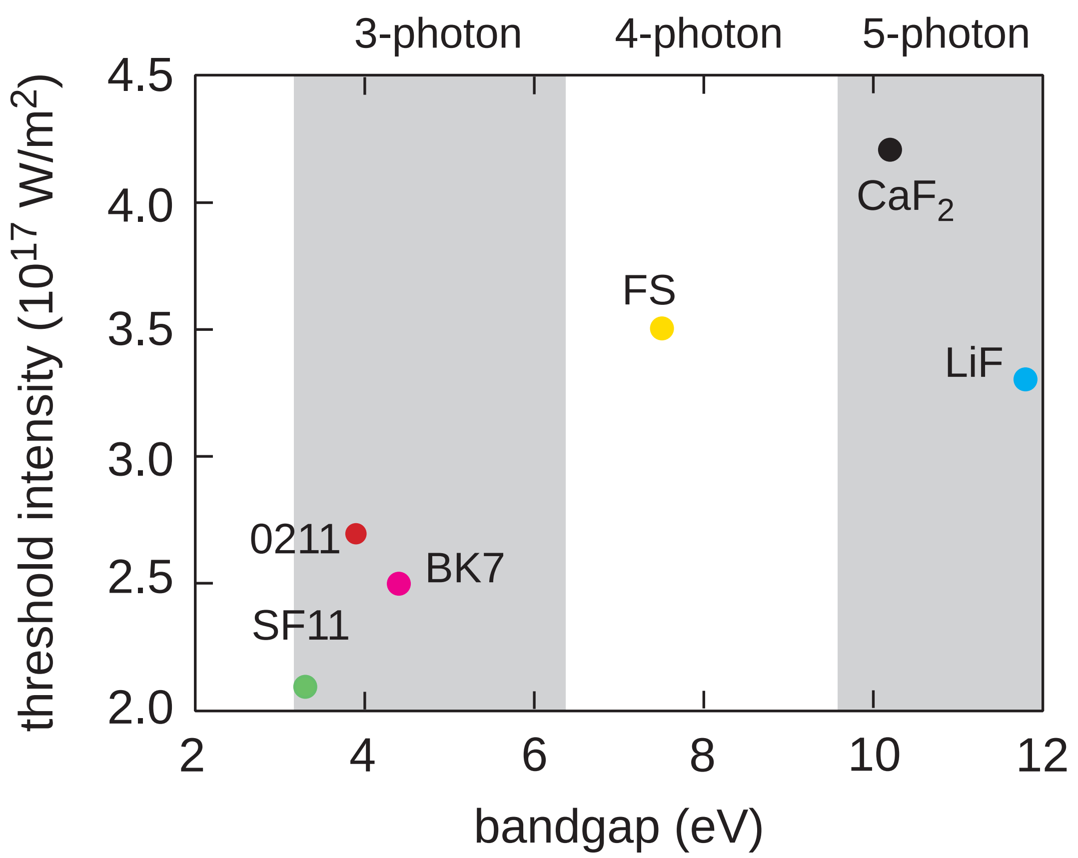
Transparent materials

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



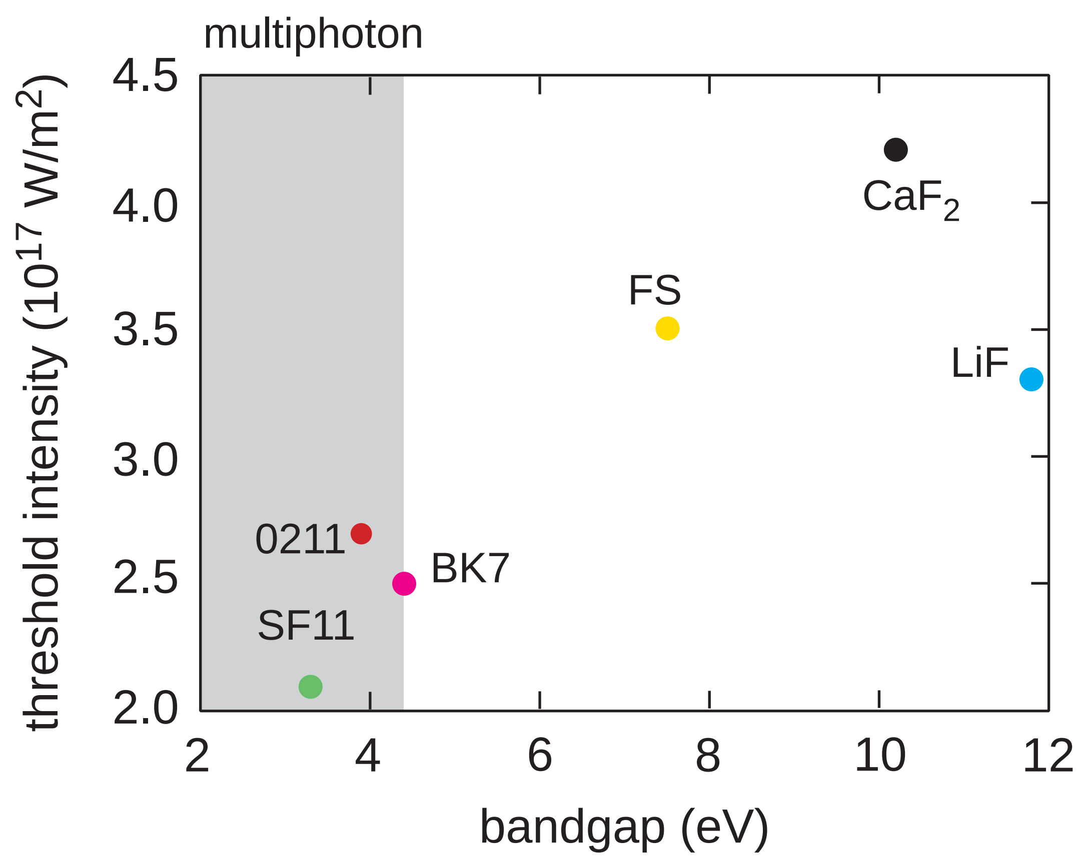
Transparent materials

would expect much more than a factor of 2



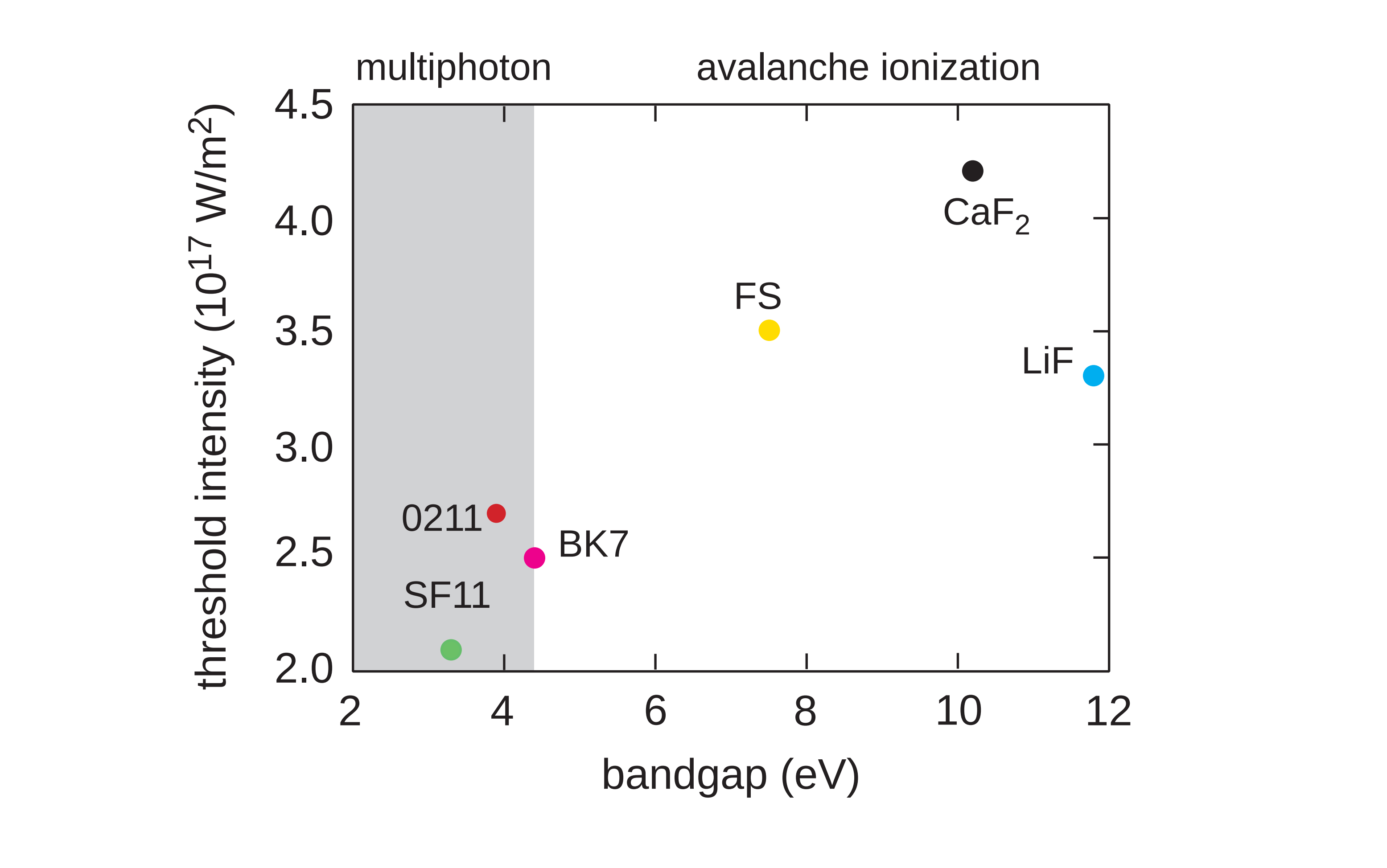
Transparent materials

critical density reached by multiphoton for low gap only



Transparent materials

avalanche ionization important at high gap



Transparent materials

what prevents damage at low NA?

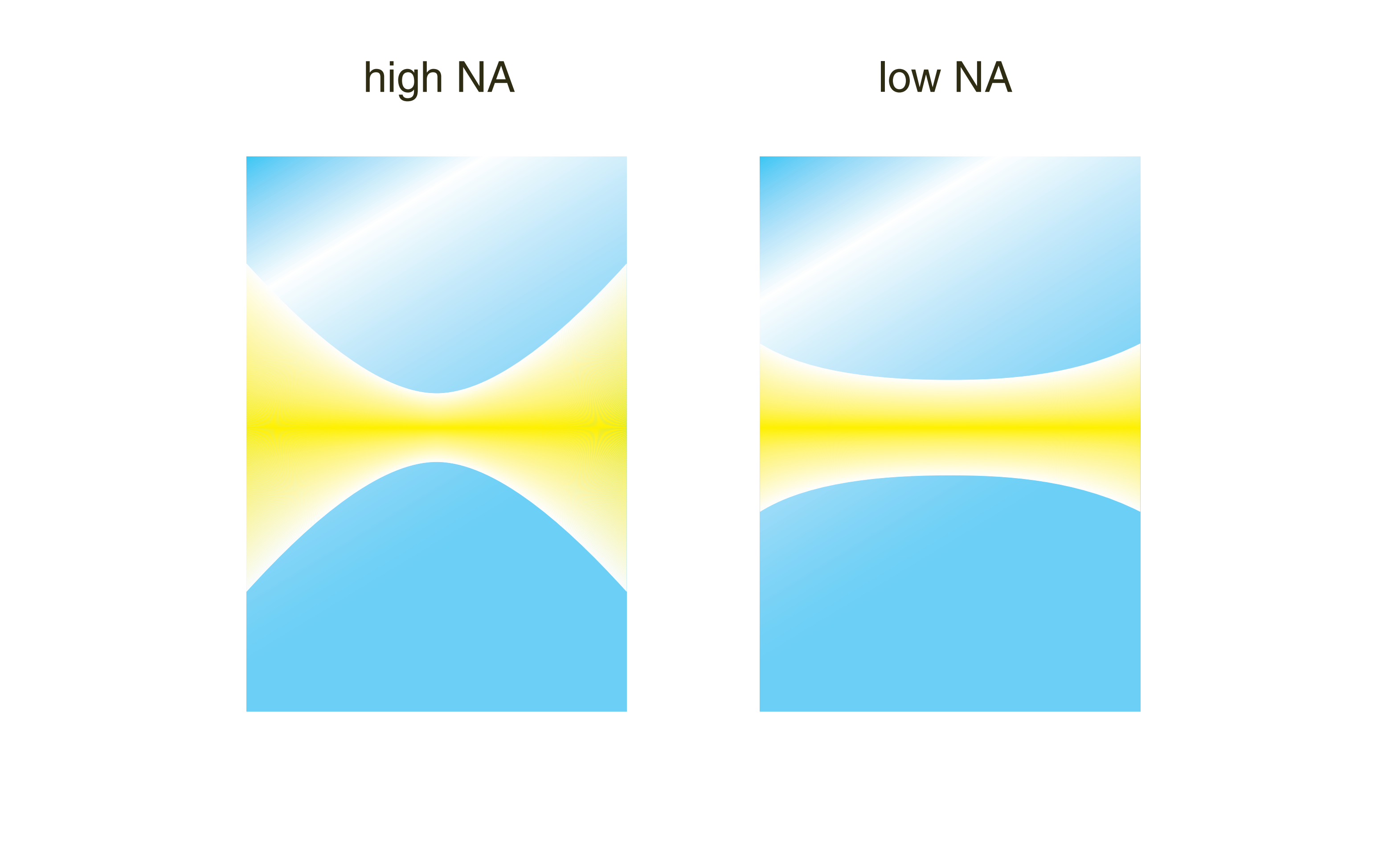
Transparent materials

Competing nonlinear effects:

- multiphoton absorption
- supercontinuum generation
- self-focusing

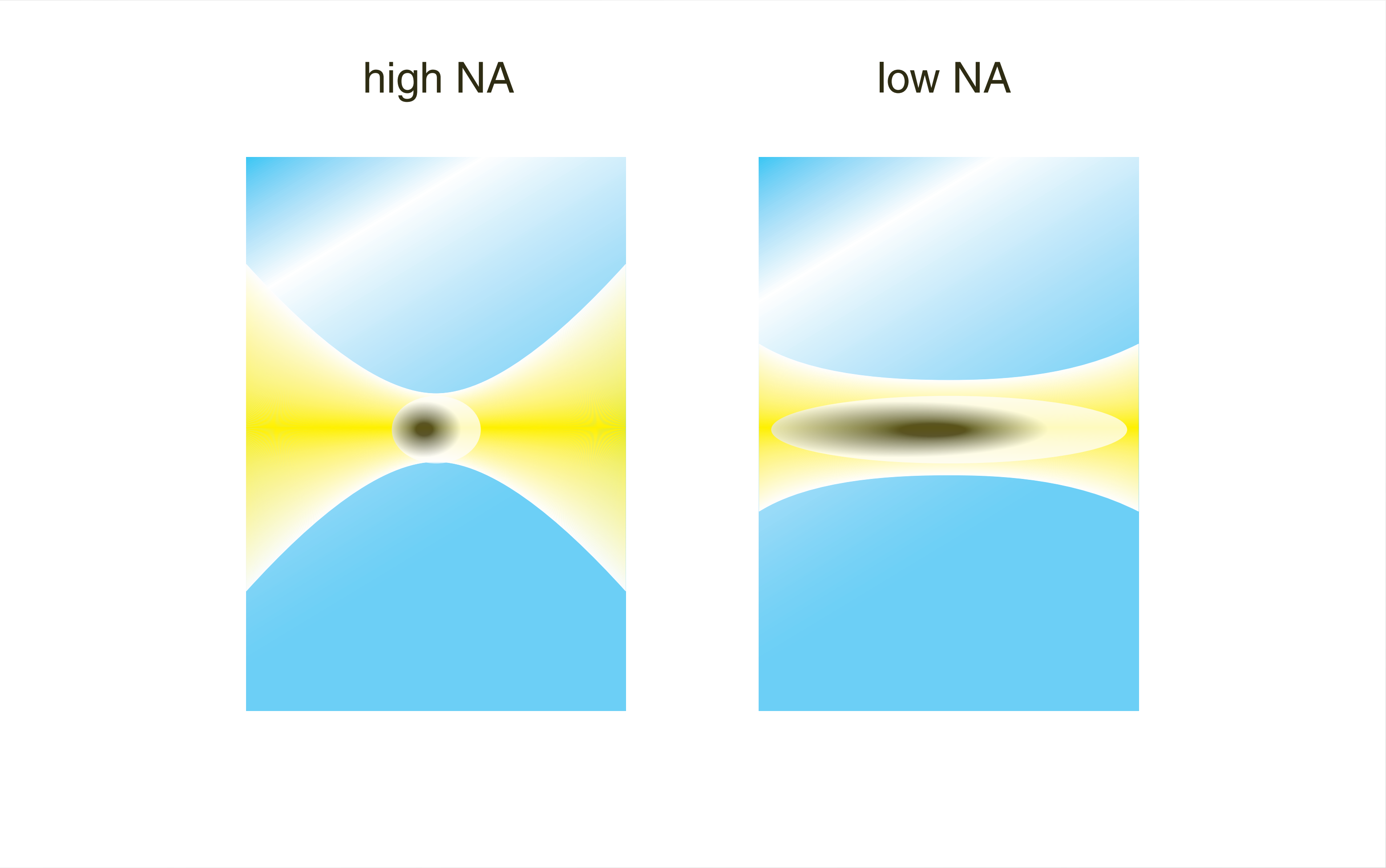
Transparent materials

why the difference?



Transparent materials

very different confocal length/interaction length

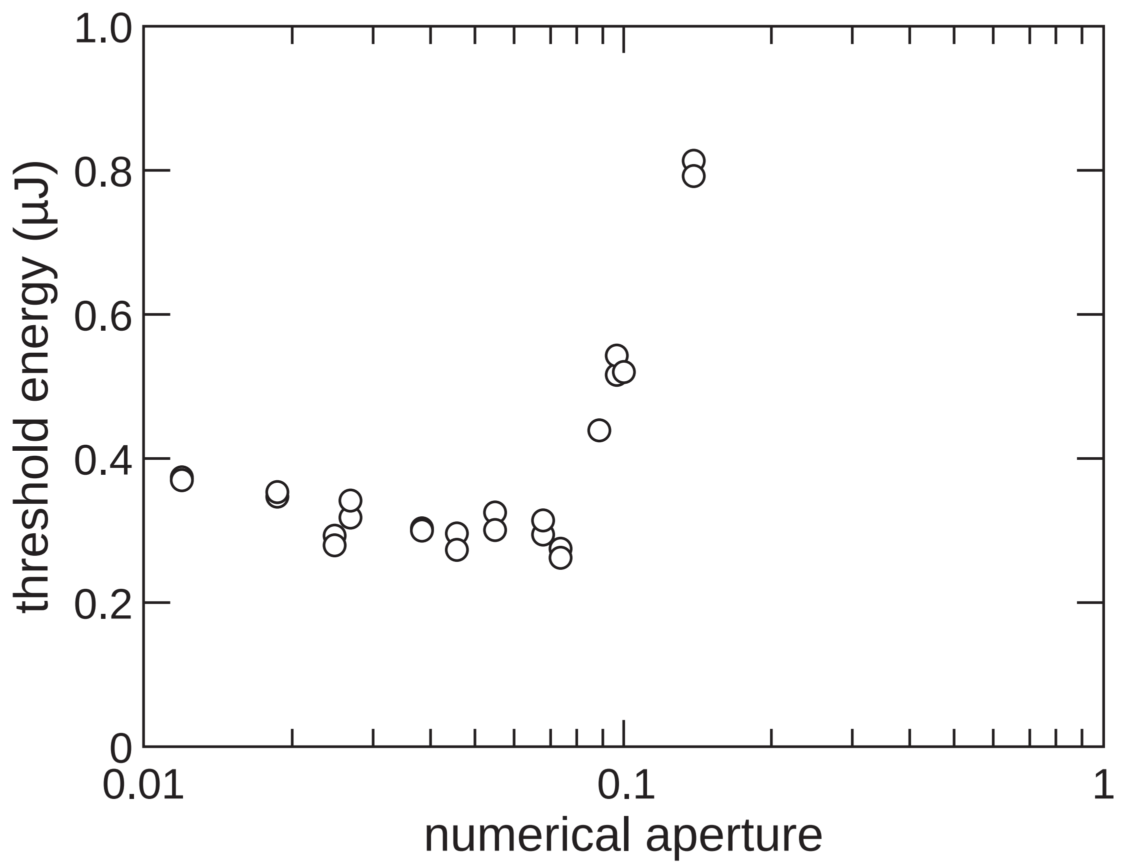


Transparent materials

high NA: interaction length too short for self-focusing

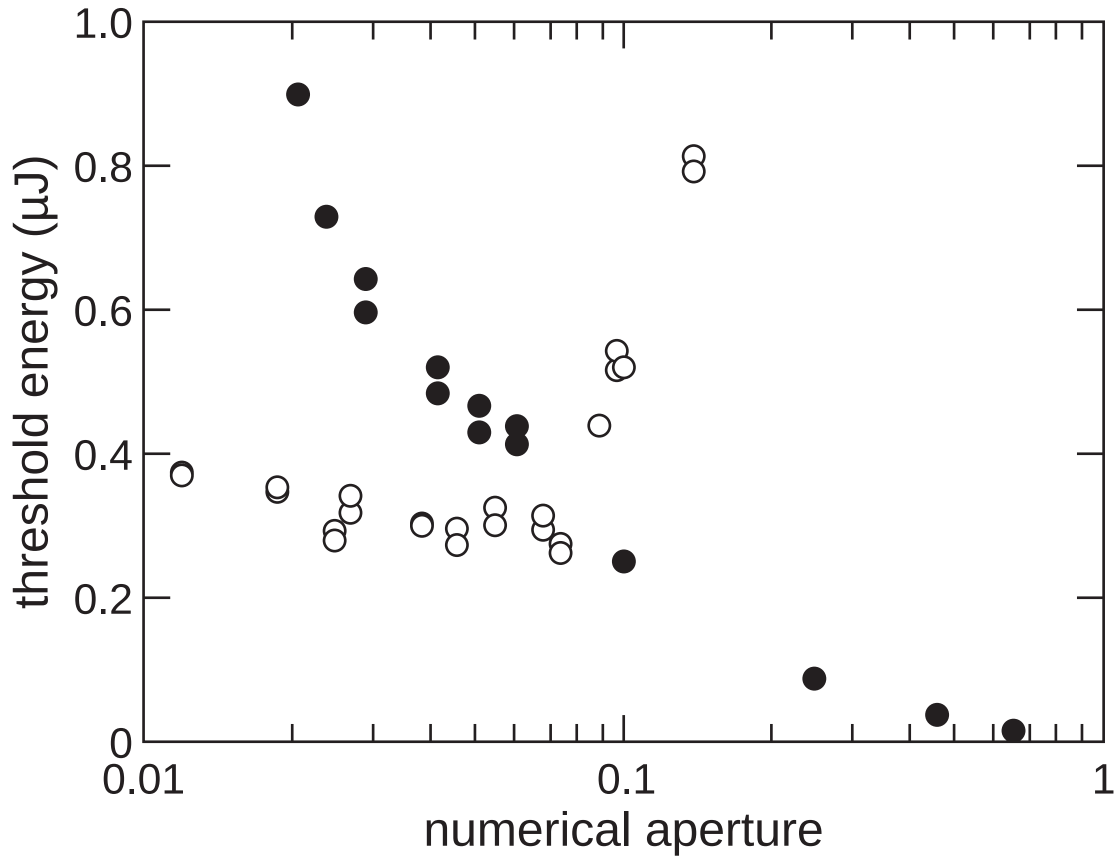
Transparent materials

threshold for supercontinuum generation



Transparent materials

threshold for damage



Transparent materials

Points to keep in mind:

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

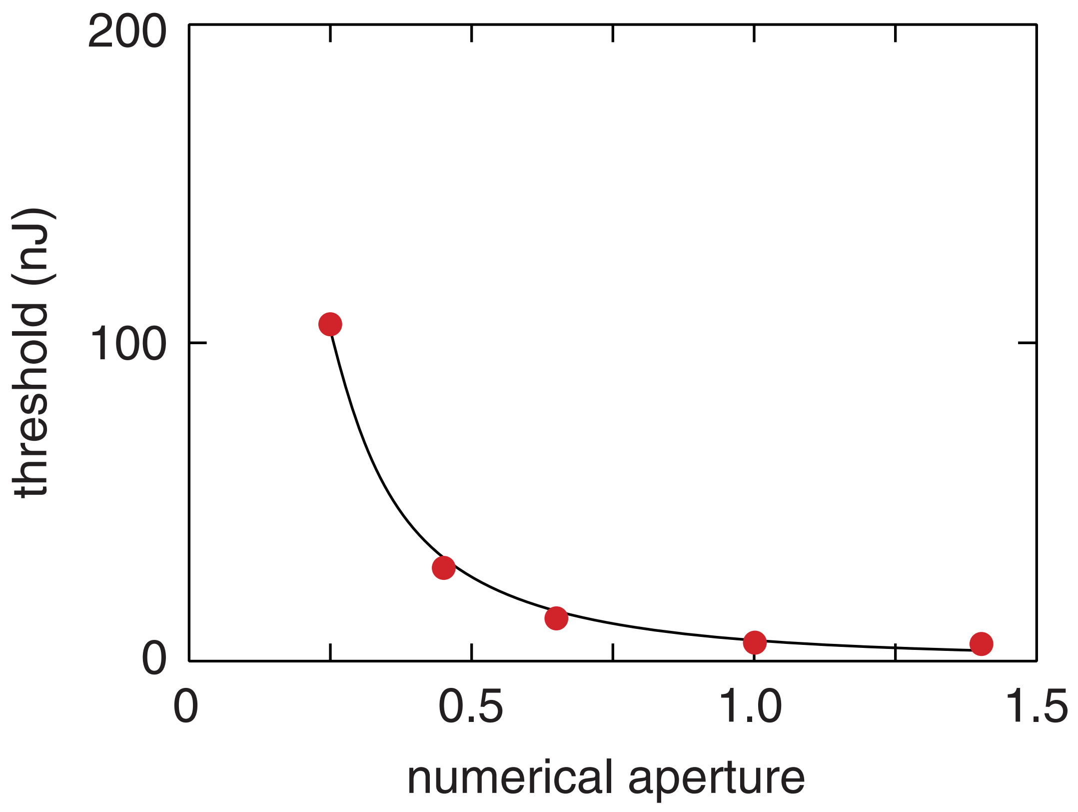
Nature Photonics **2**, 219 (2008)

Outline

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

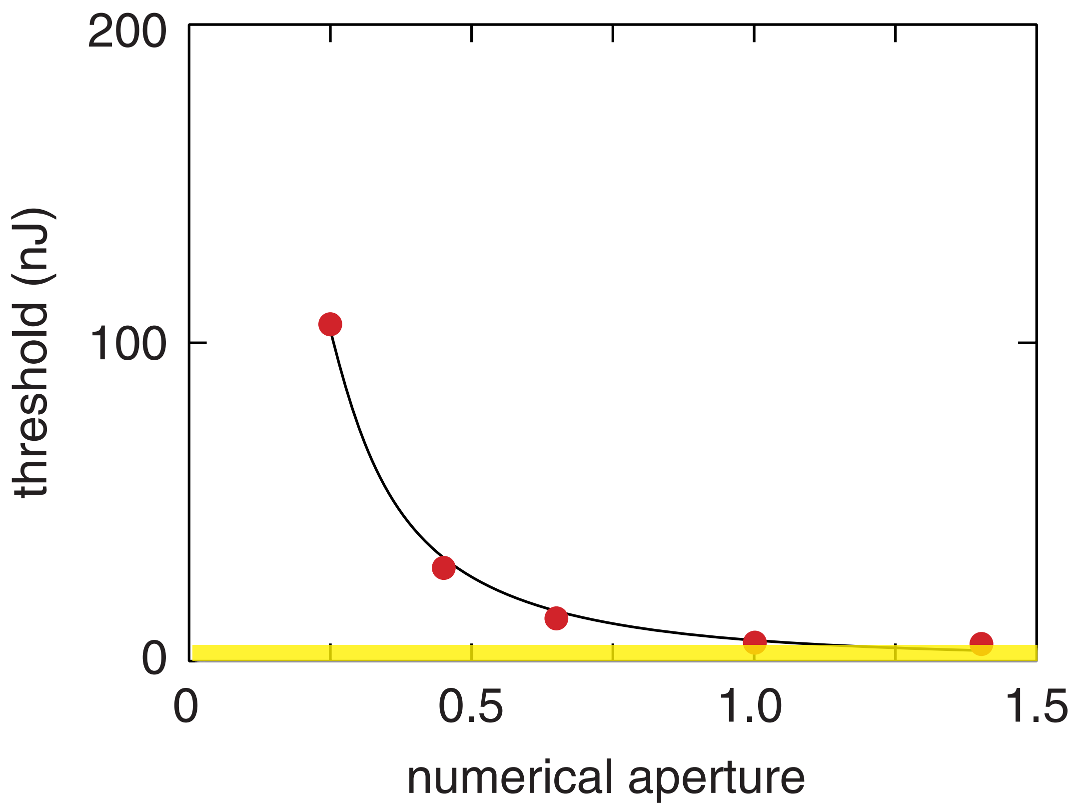
Bulk micromachining

threshold decreases with increasing numerical aperture



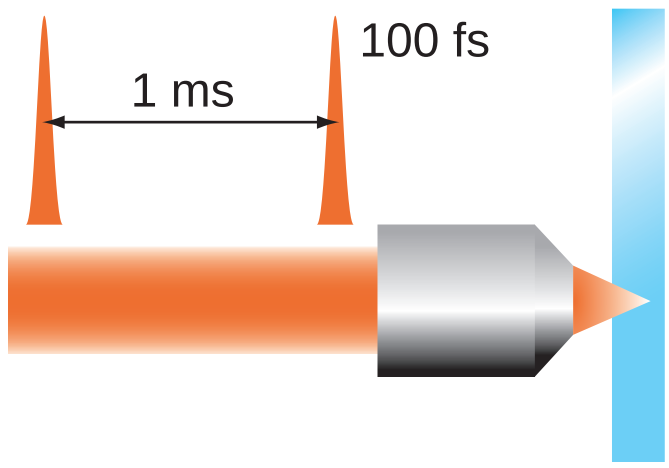
Bulk micromachining

less than 10 nJ at high numerical aperture!



Bulk micromachining

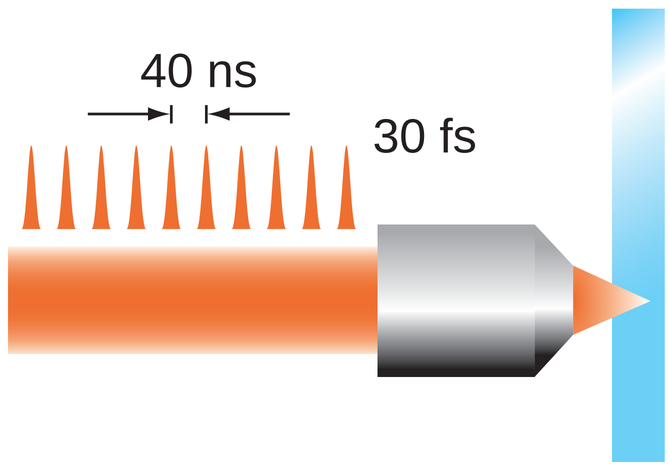
amplified laser: 1 kHz, 1 mJ



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

Bulk micromachining

long cavity oscillator: 25 MHz, 25 nJ



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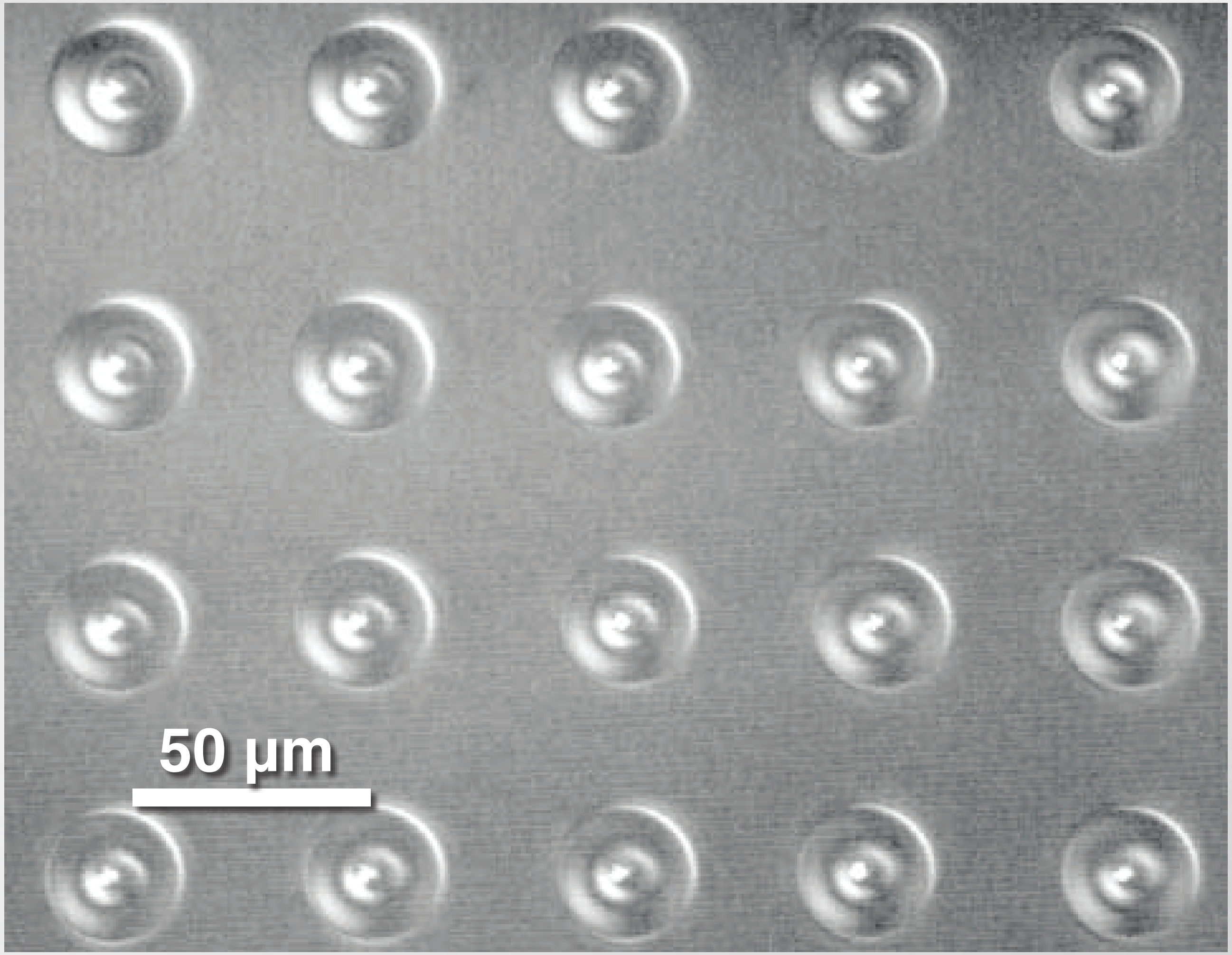
Bulk micromachining



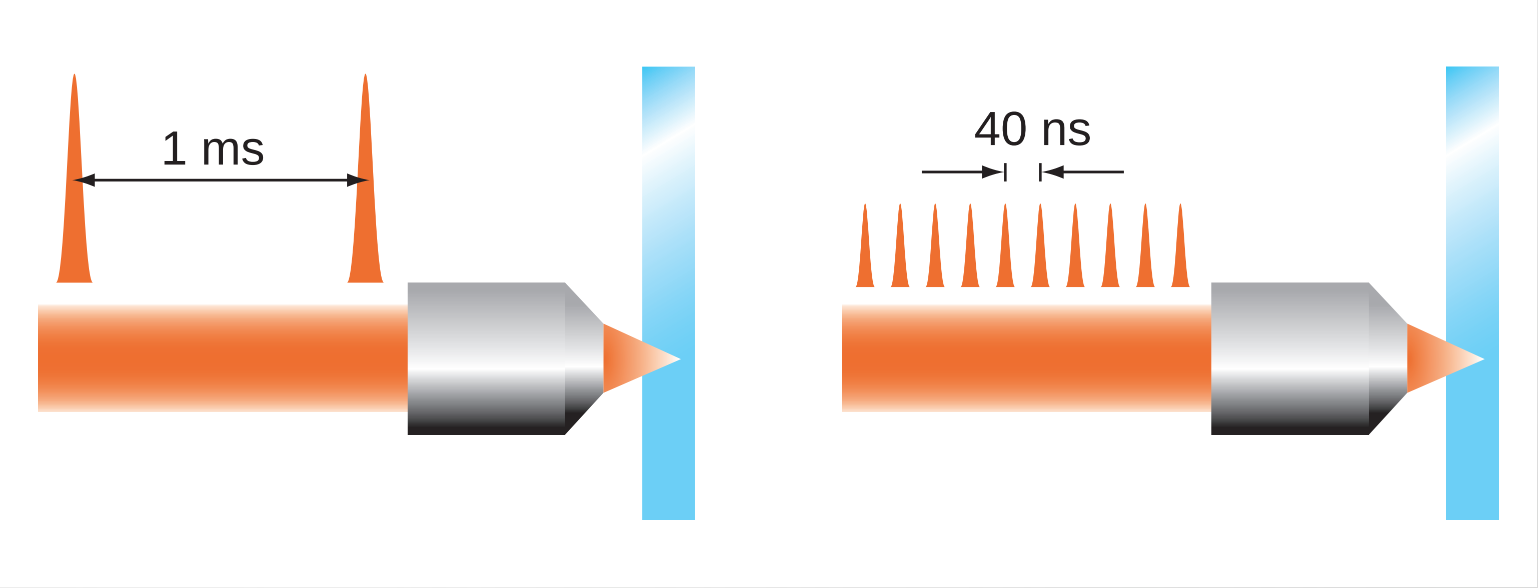
Bulk micromachining

High repetition-rate micromachining:

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

Bulk micromachining

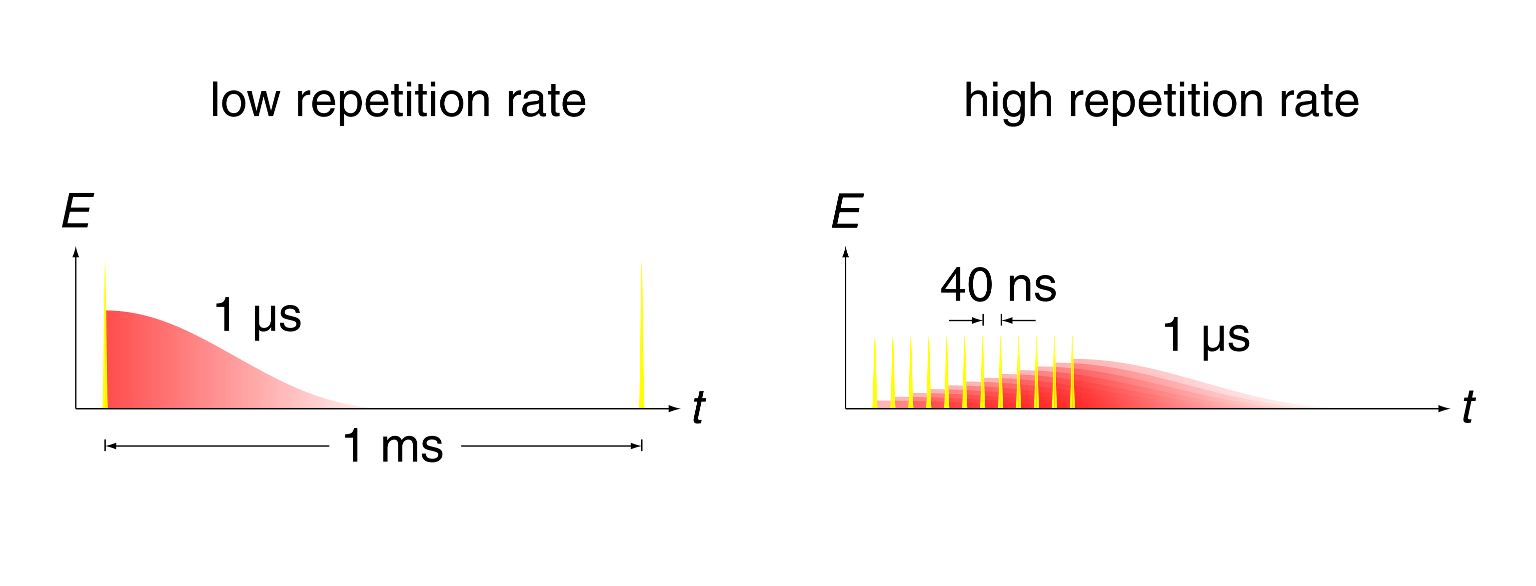
amplified laser | oscillator



repetitive | cumulative

Bulk micromachining

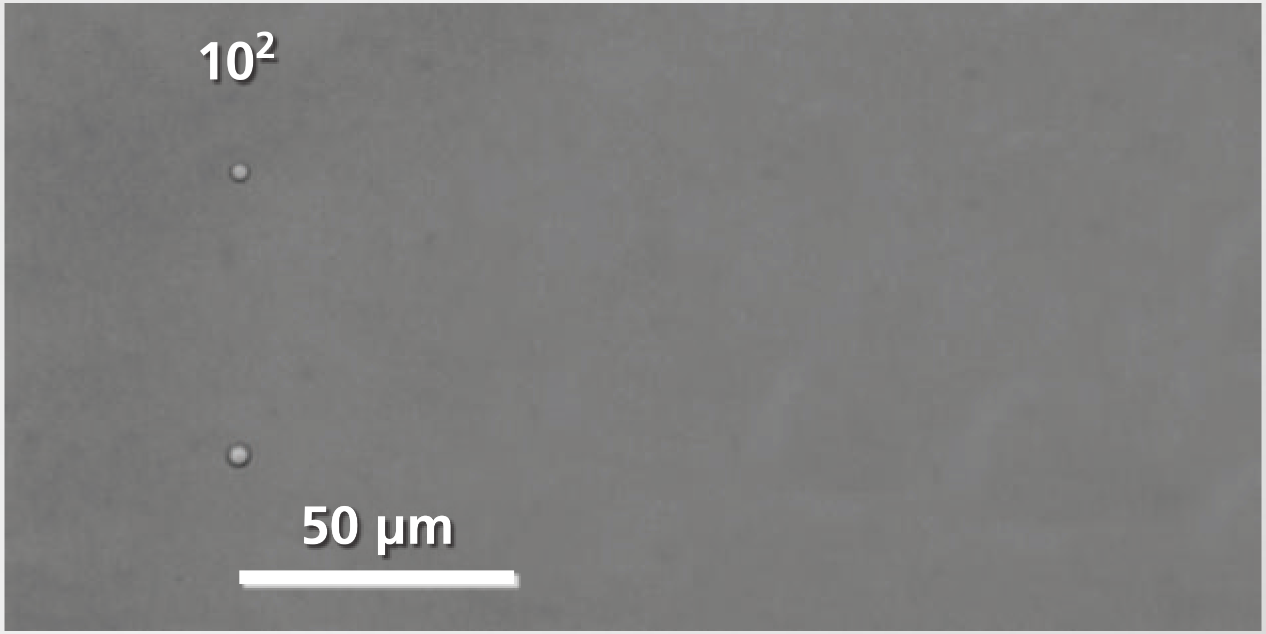
amplified laser | **oscillator**



repetitive | **cumulative**

Bulk micromachining

the longer the irradiation…



Bulk micromachining

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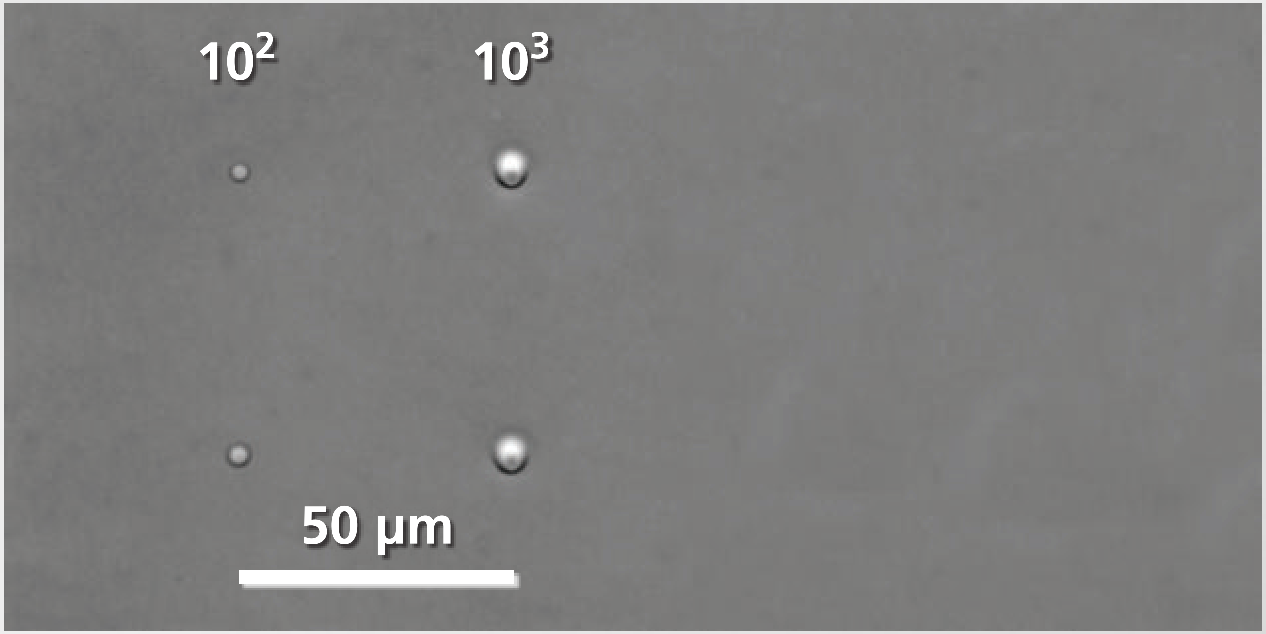

Bulk micromachining

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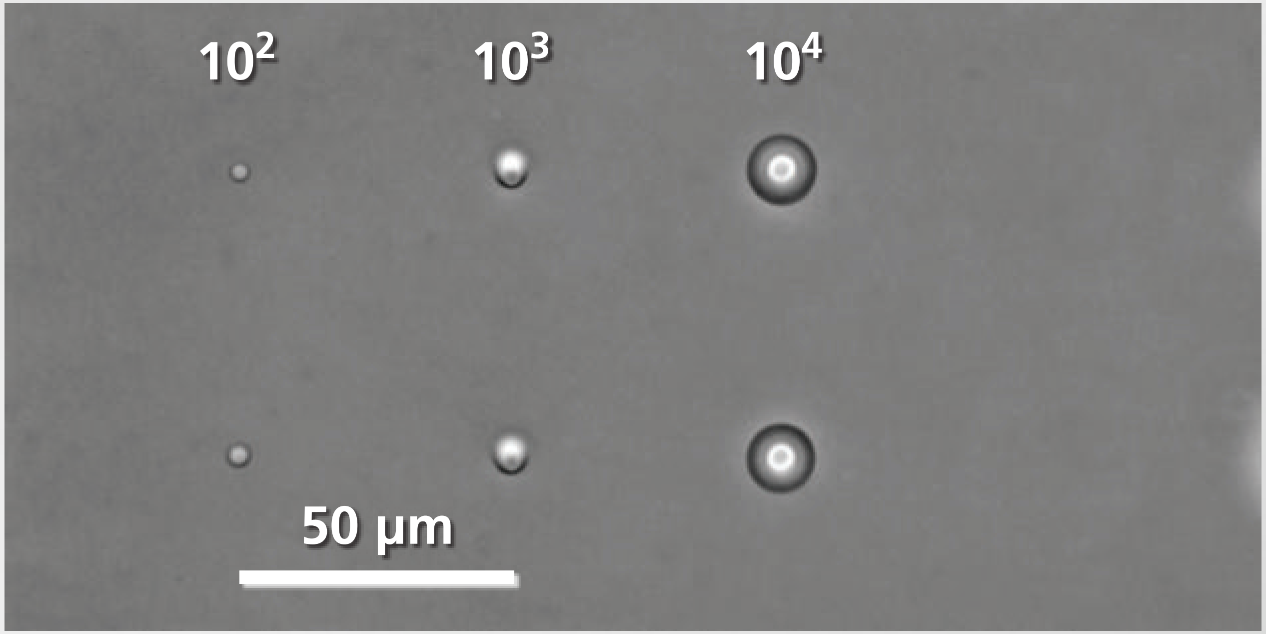
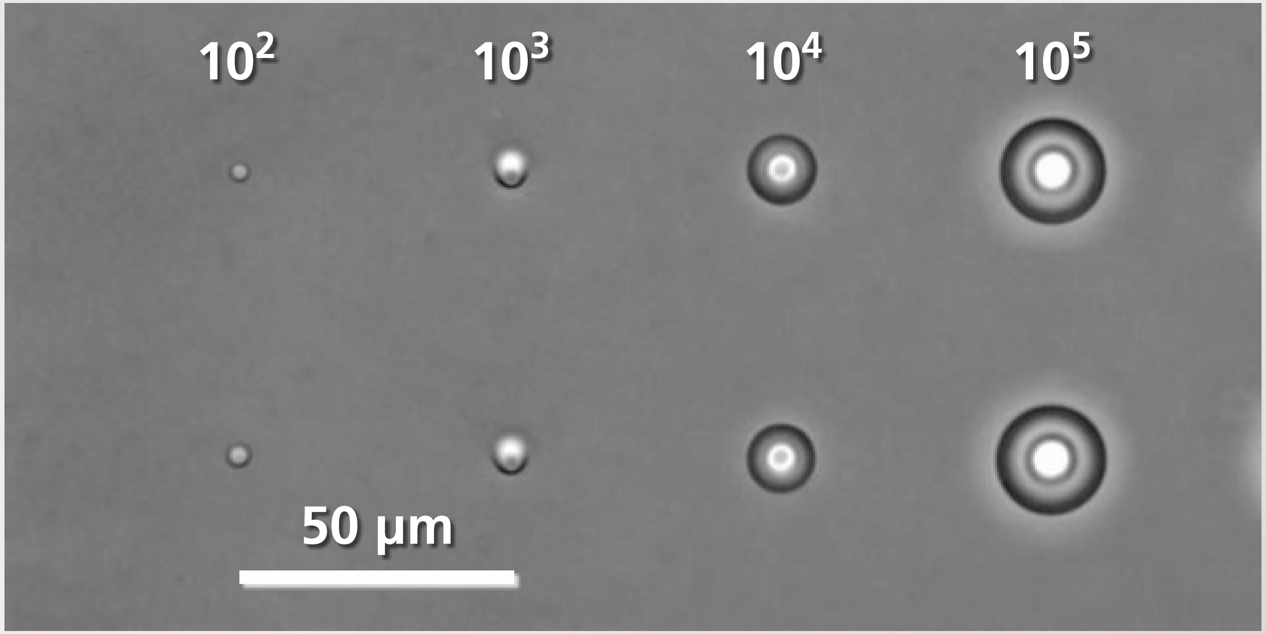


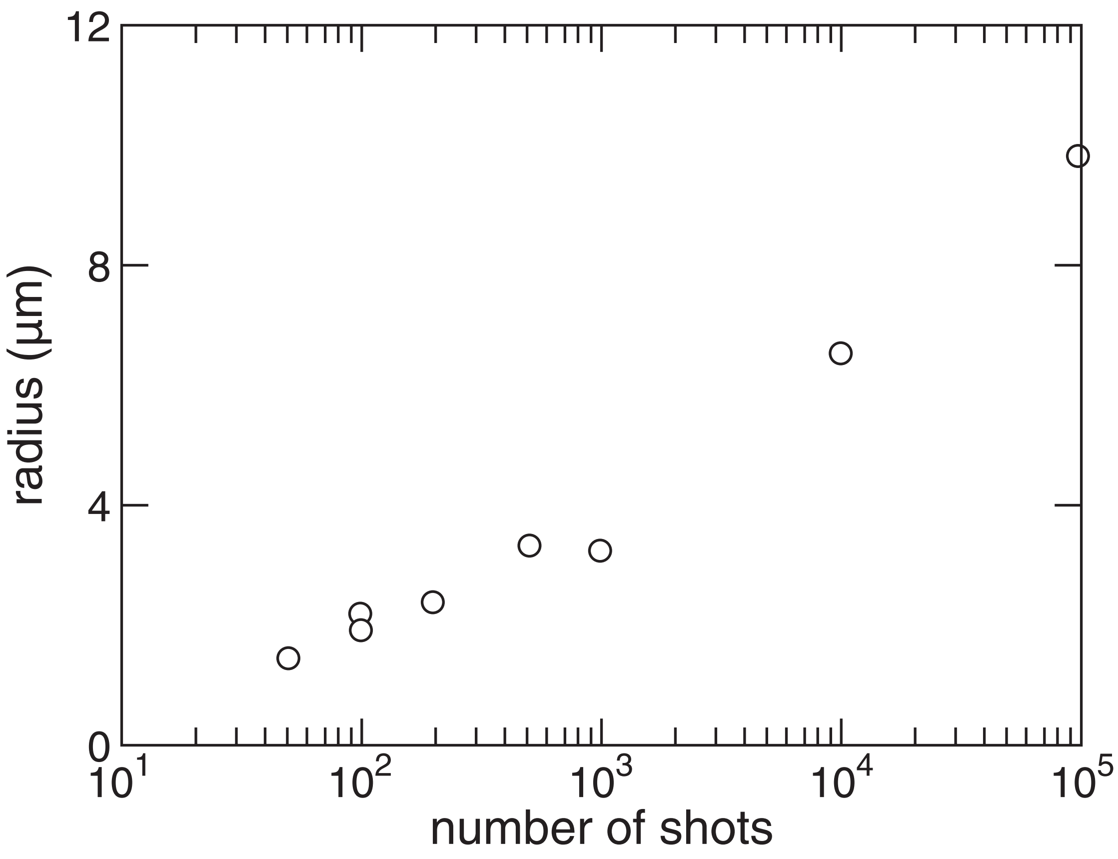
Bulk micromachining

the longer the irradiation…



… the larger the radius

Bulk micromachining

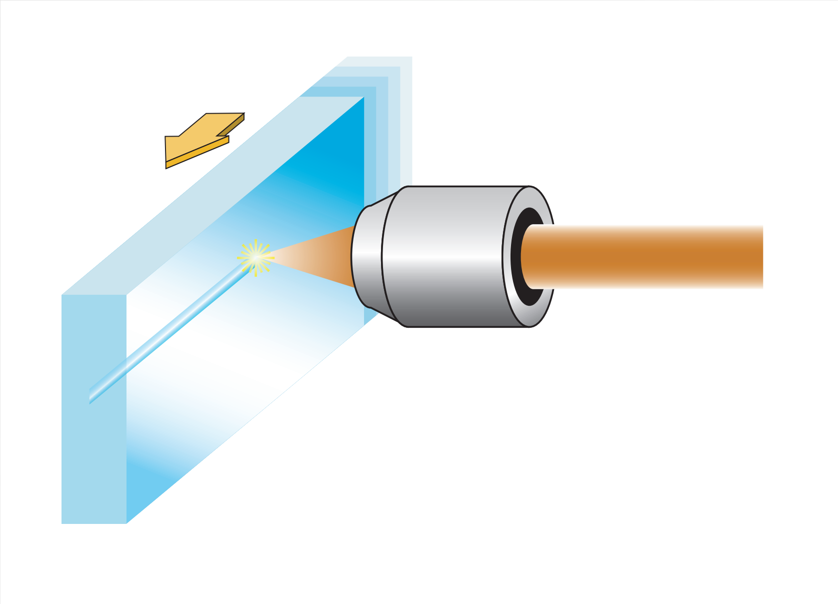


Bulk micromachining

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

Bulk micromachining

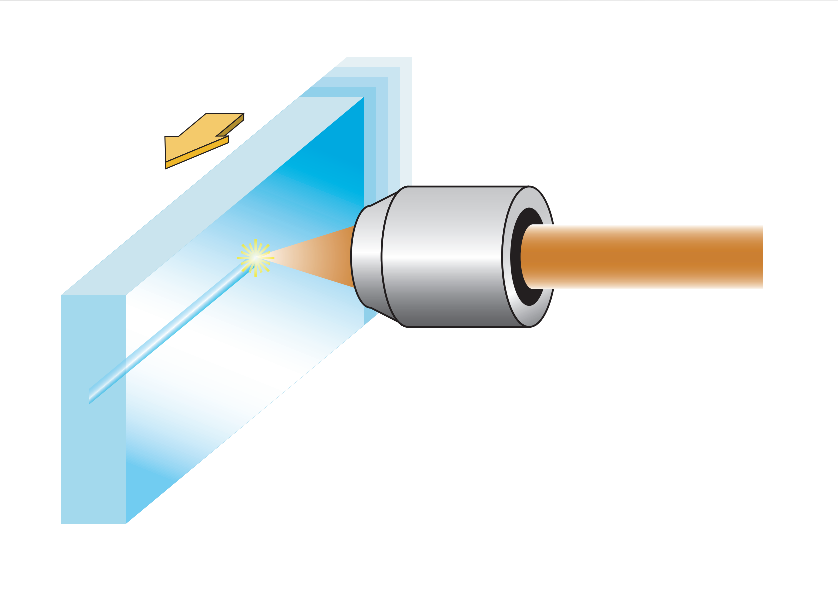
waveguide micromachining

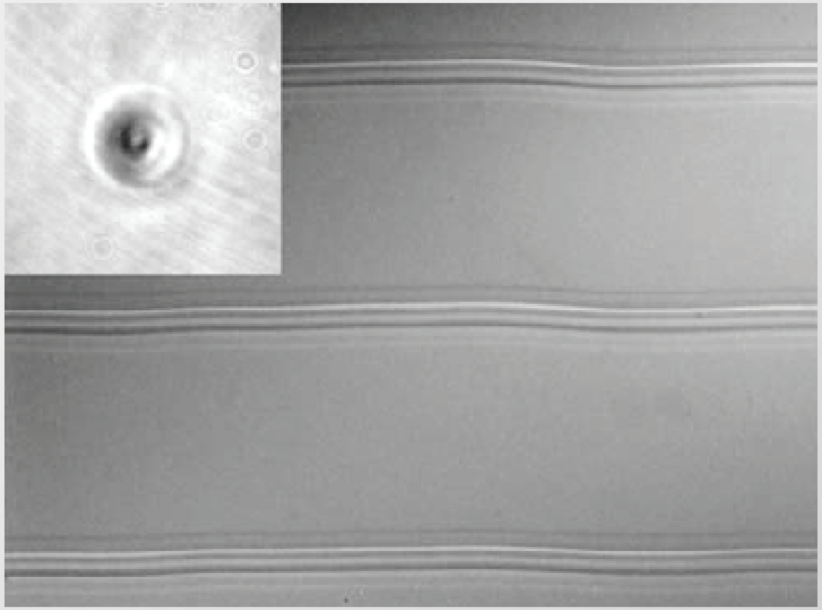


Opt. Lett. **26**, 93 (2001)

Bulk micromachining

waveguide micromachining

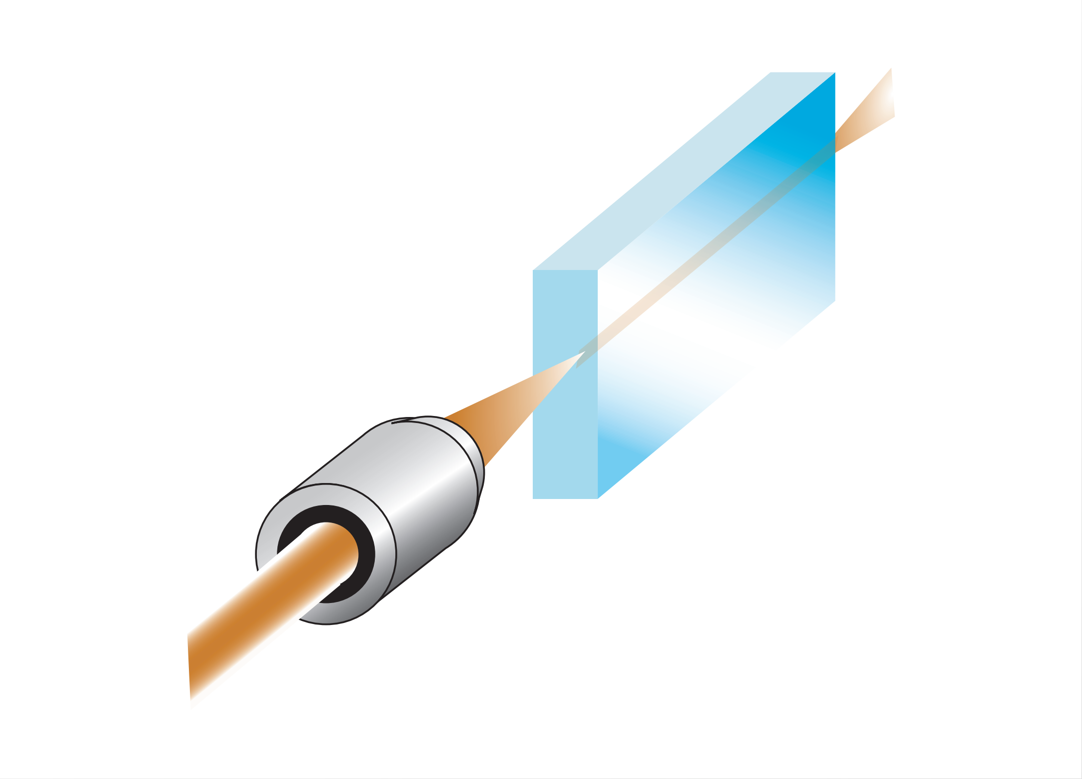




Opt. Lett. **26**, 93 (2001)

Bulk micromachining

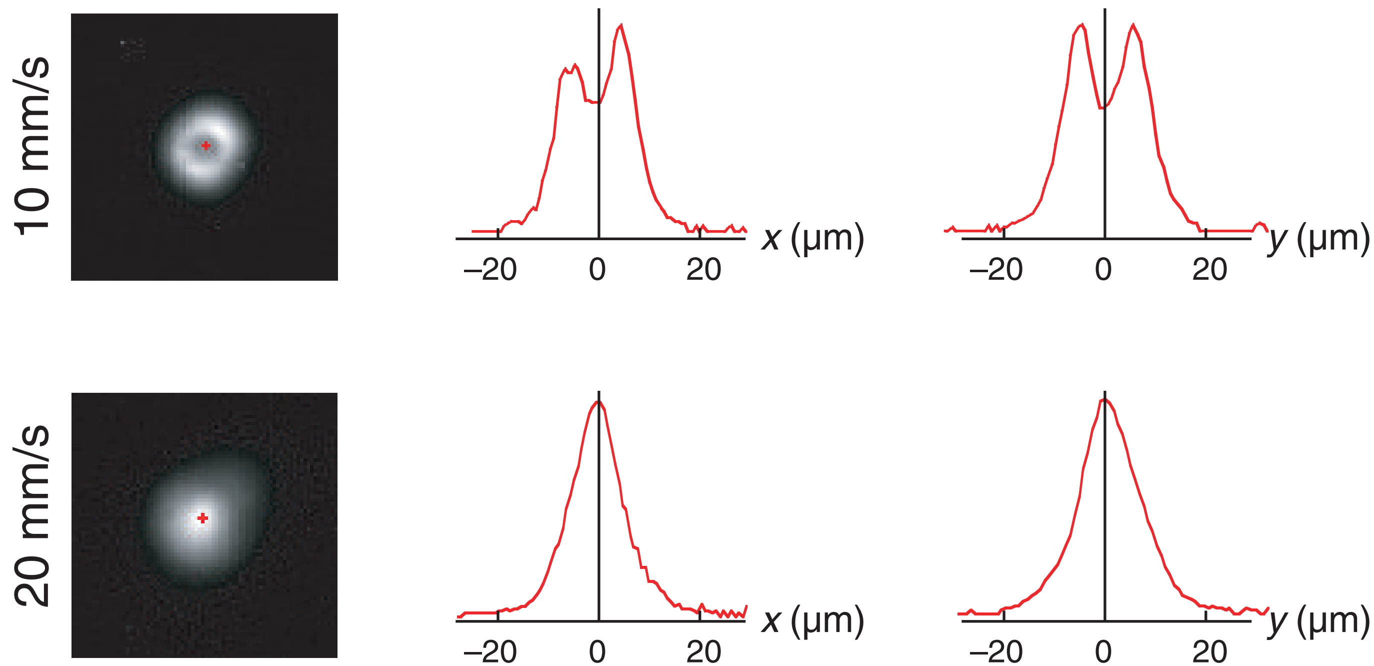
structures guide light



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

Bulk micromachining

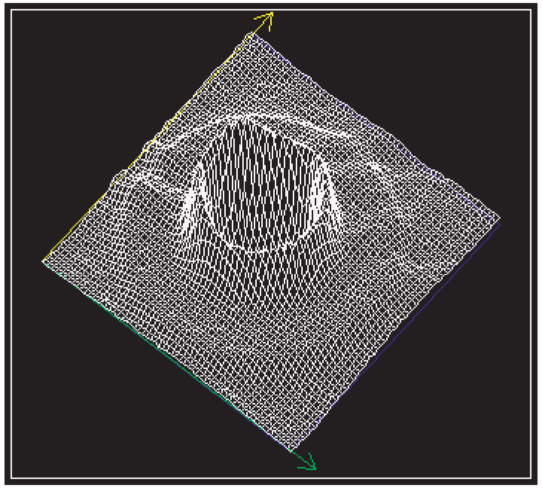
near-field profiles

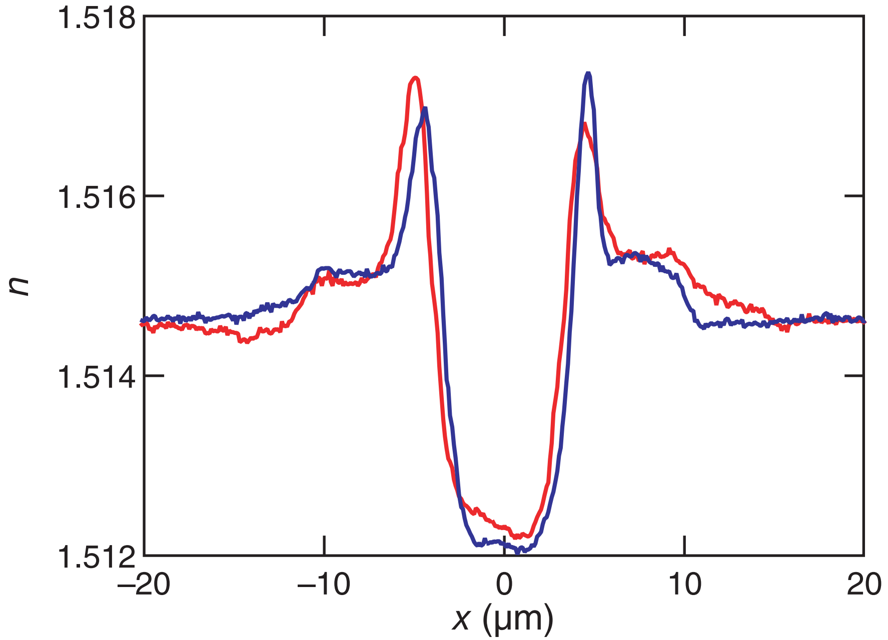


Sagitta, Inc.

Bulk micromachining

index profile at 2.5 mm/s





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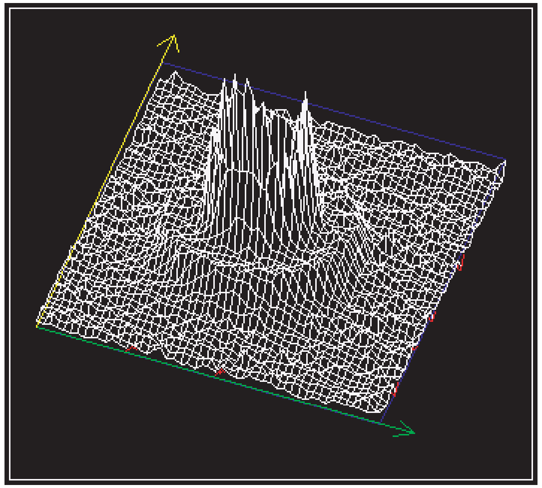
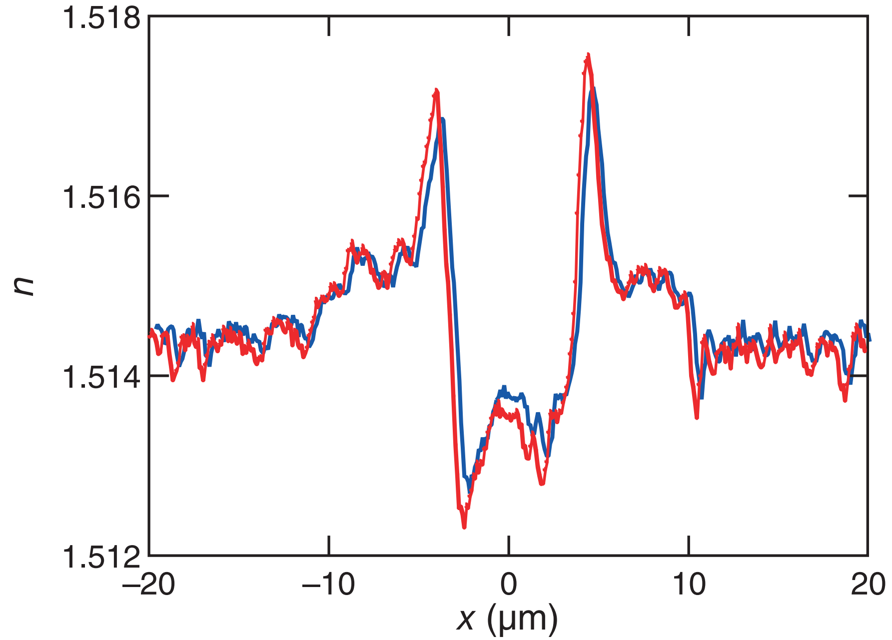
Bulk micromachining

index profile at 10 mm/s

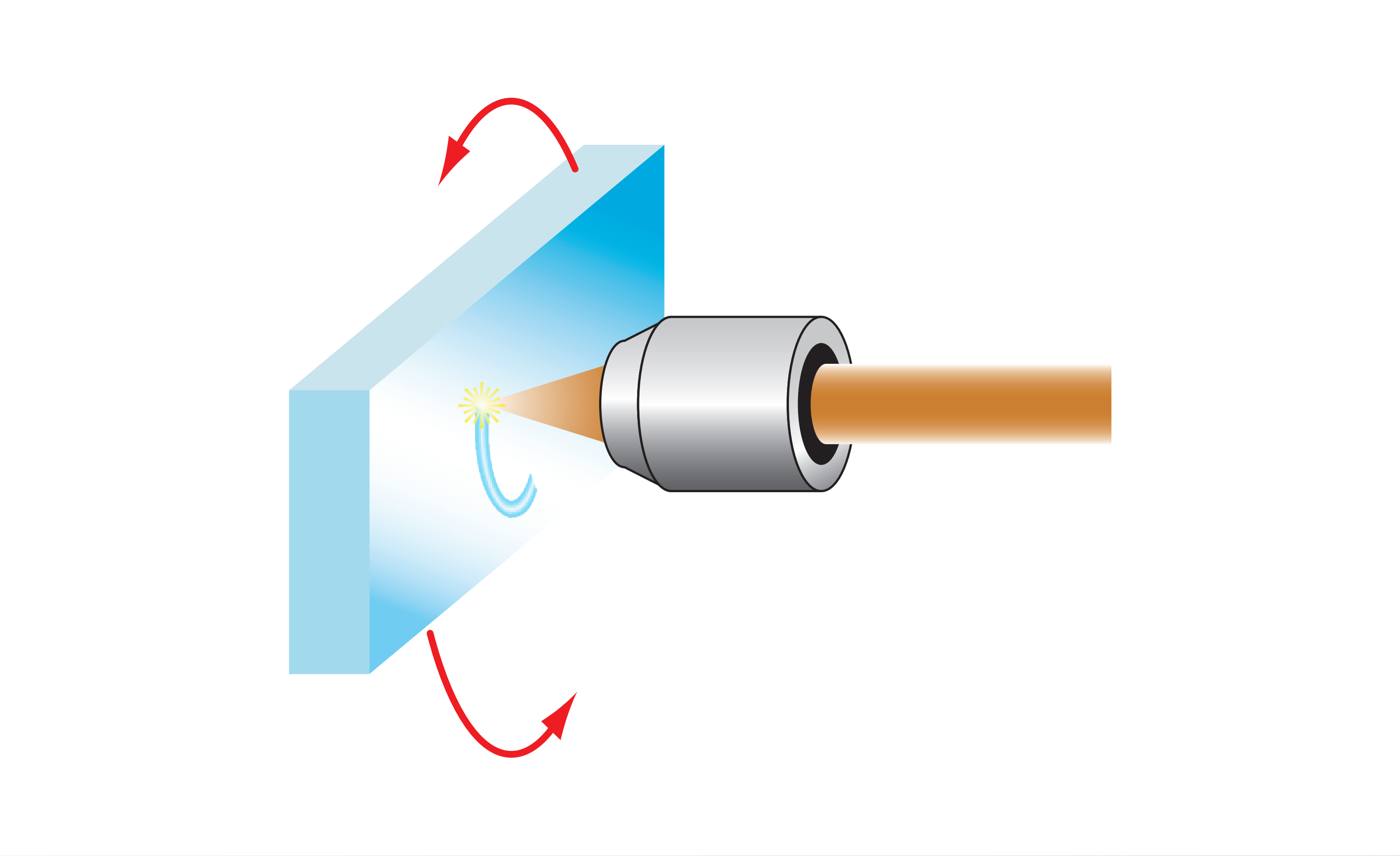




Sagitta, Inc.

Bulk micromachining

curved waveguides



Bulk micromachining

curved waveguides

Bulk micromachining

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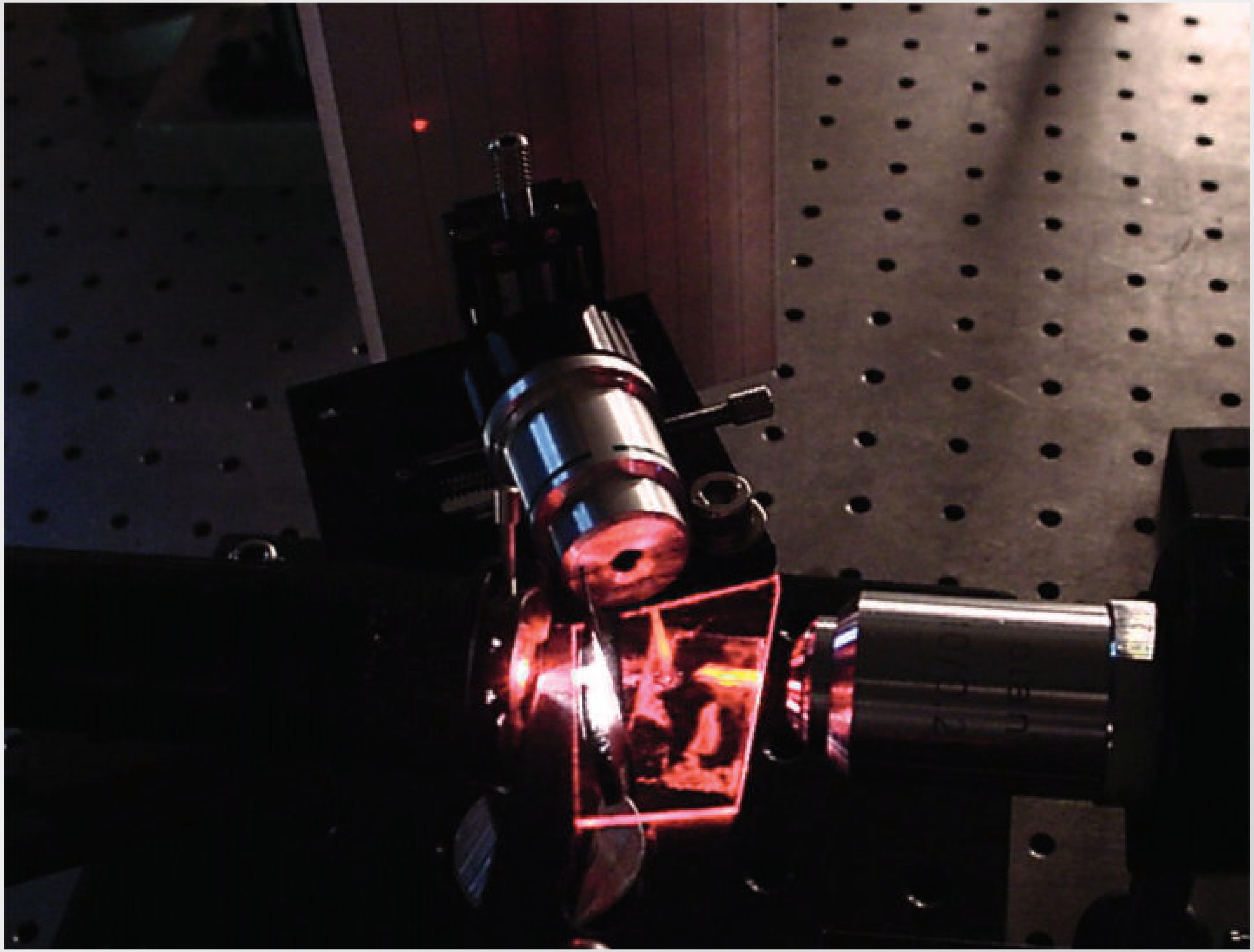
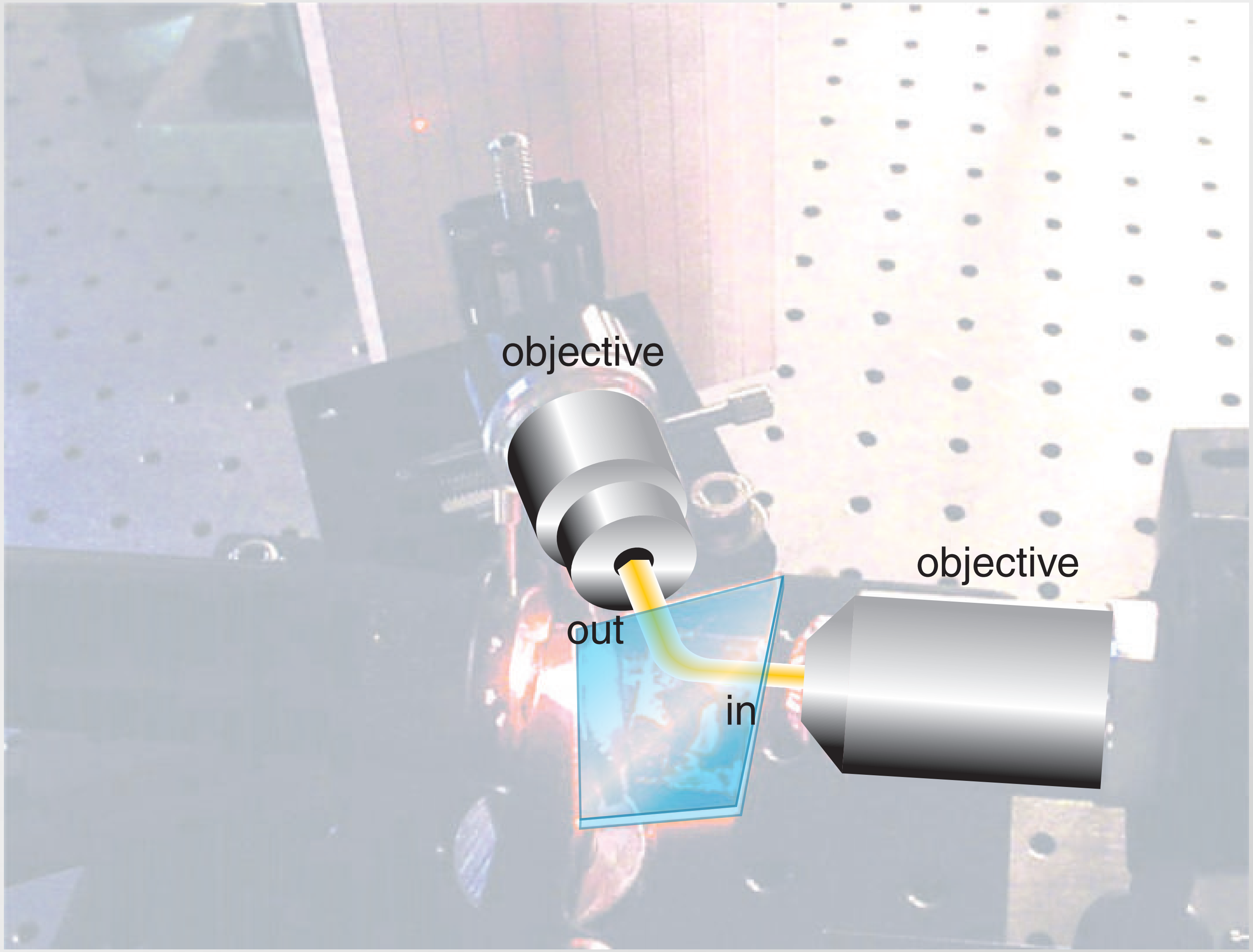


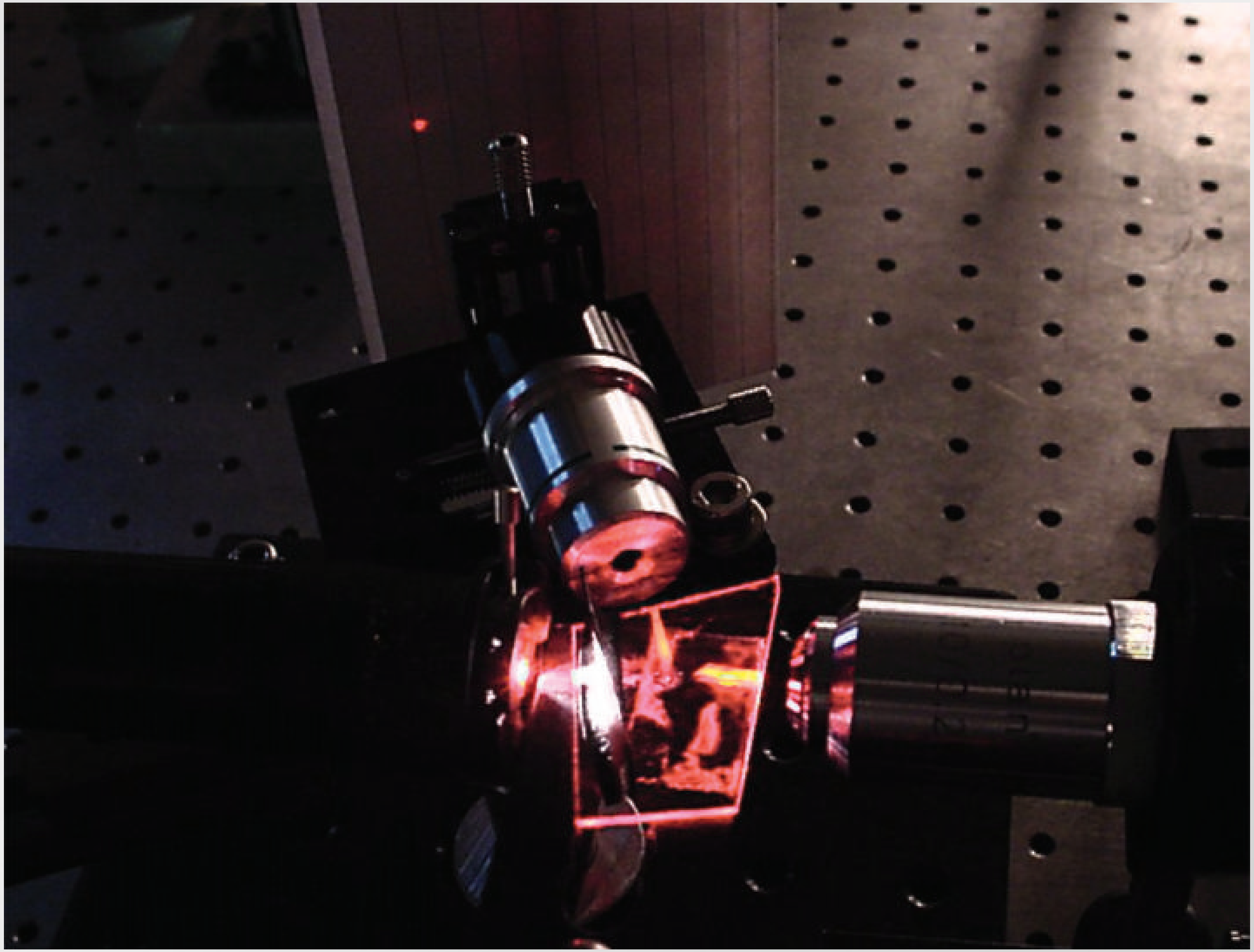
Bulk micromachining

curved waveguides



Bulk micromachining

curved waveguides



Bulk micromachining

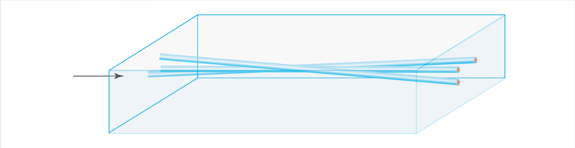
photonic fabrication techniques

	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

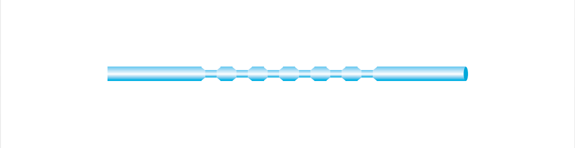
Bulk micromachining

photonic devices

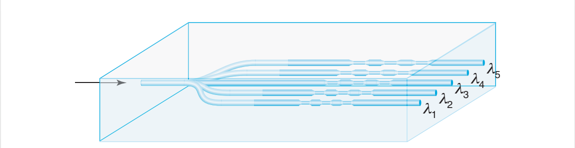
3D splitter



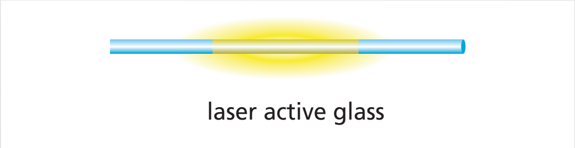
Bragg grating



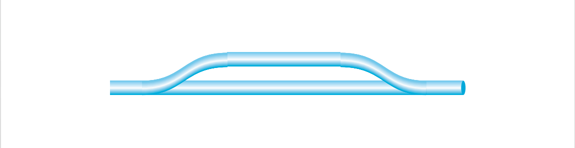
demultiplexer



amplifier



interferometer



Bulk micromachining

all-optical sensor

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

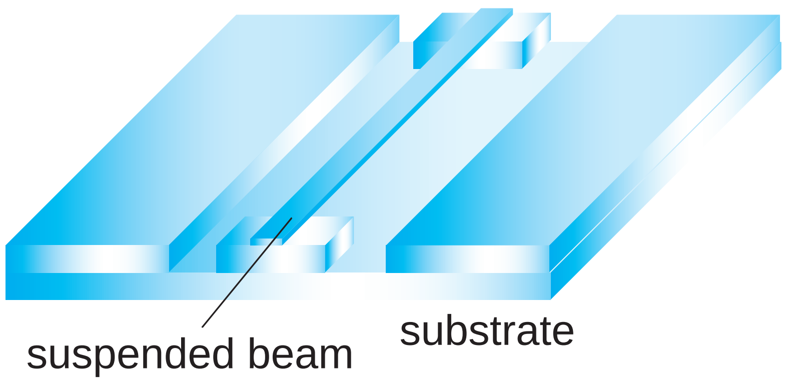
Bulk micromachining

all-optical sensor

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

Bulk micromachining

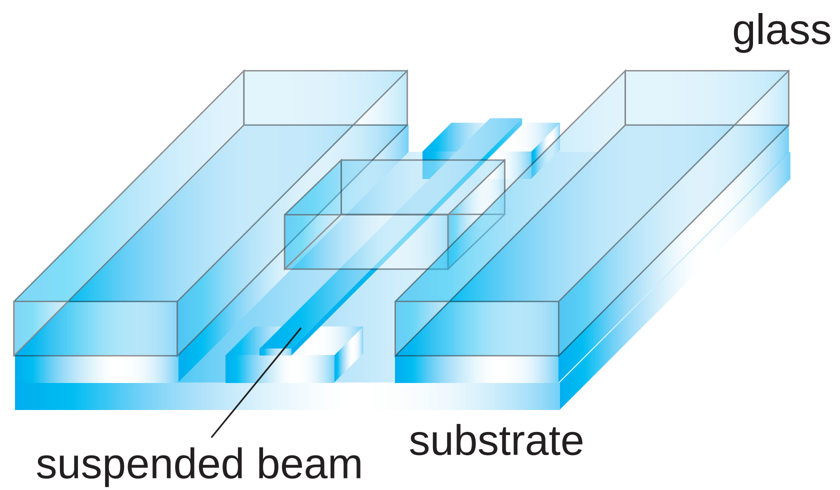
all-optical sensor



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

Bulk micromachining

all-optical sensor



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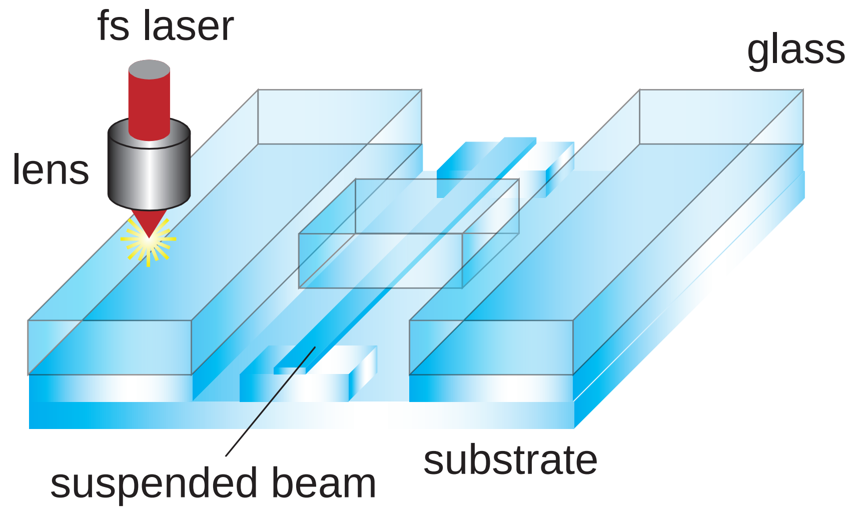
Bulk micromachining

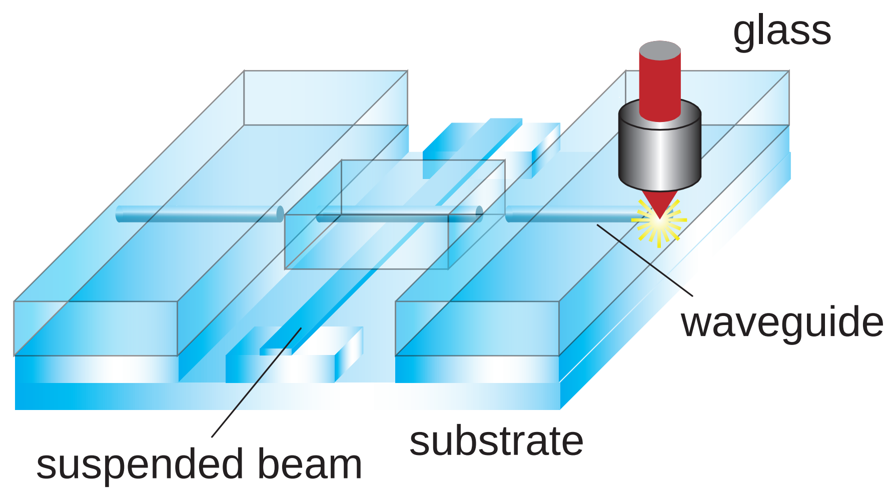
all-optical sensor



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

Bulk micromachining

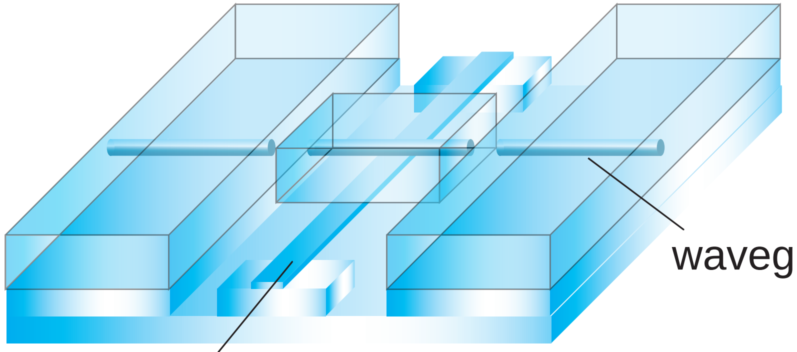
all-optical sensor



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

Bulk micromachining

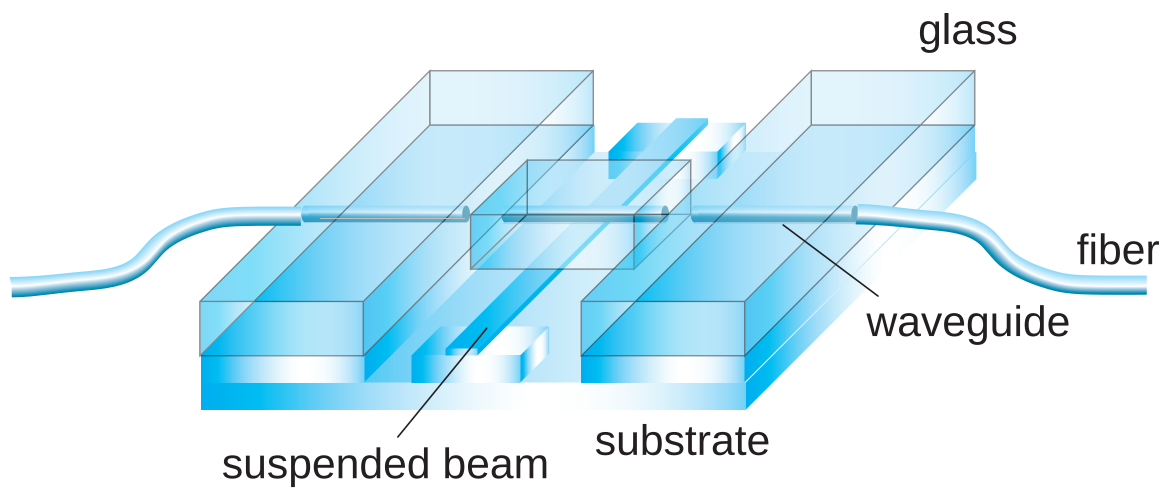
all-optical sensor



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

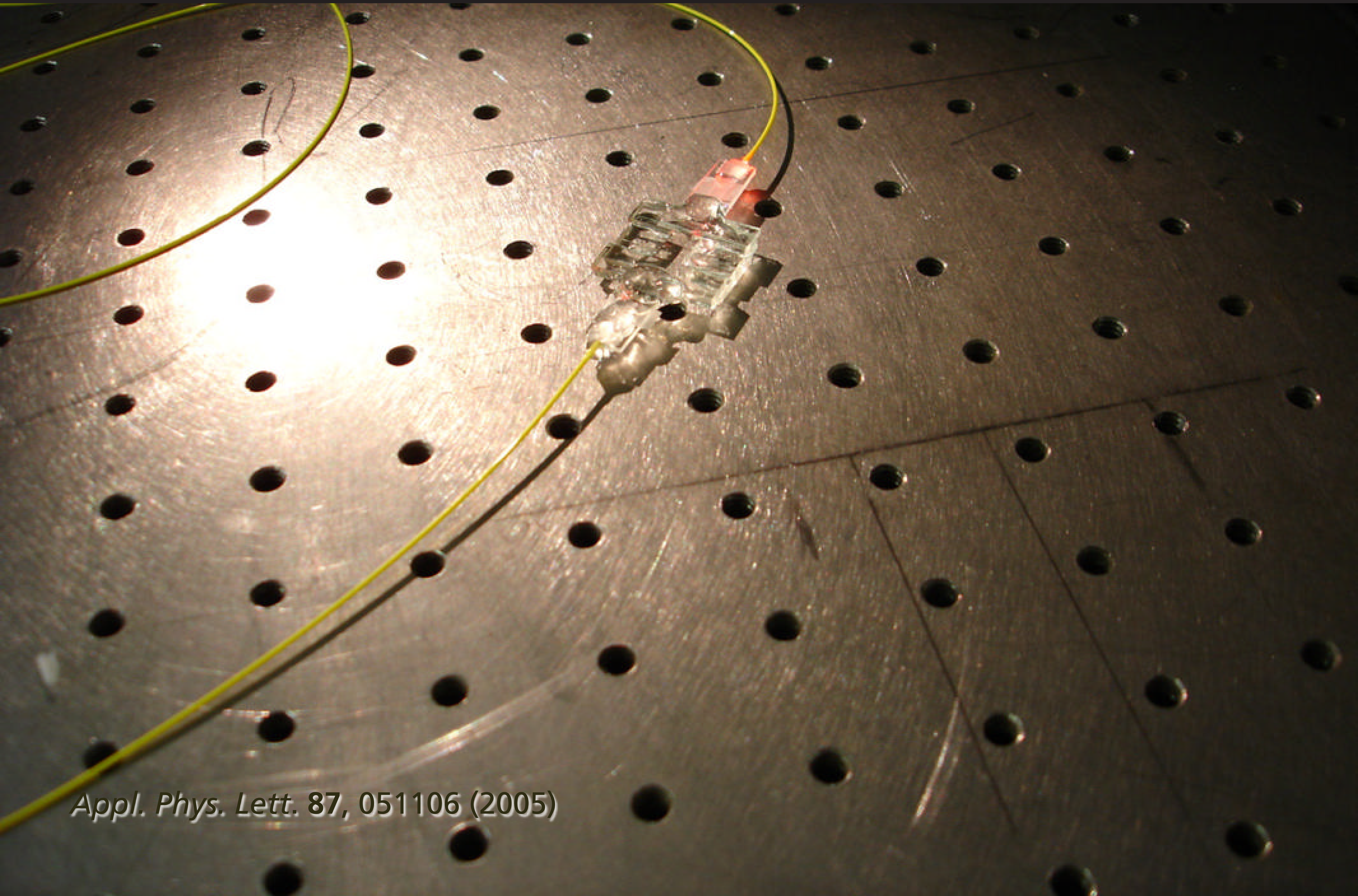
Bulk micromachining

all-optical sensor



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

Bulk micromachining

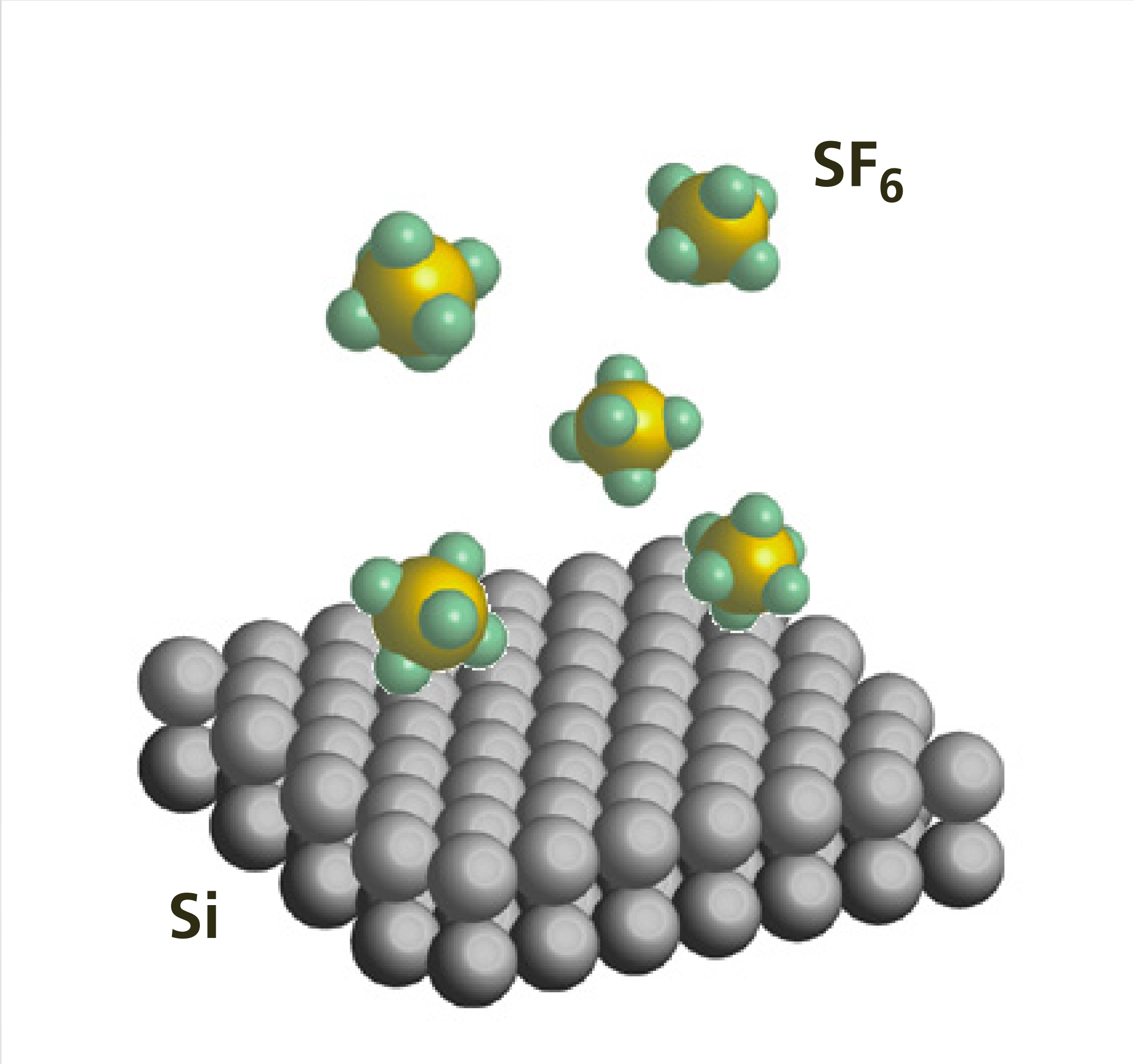


Appl. Phys. Lett. **87**, 051106 (2005)

Outline

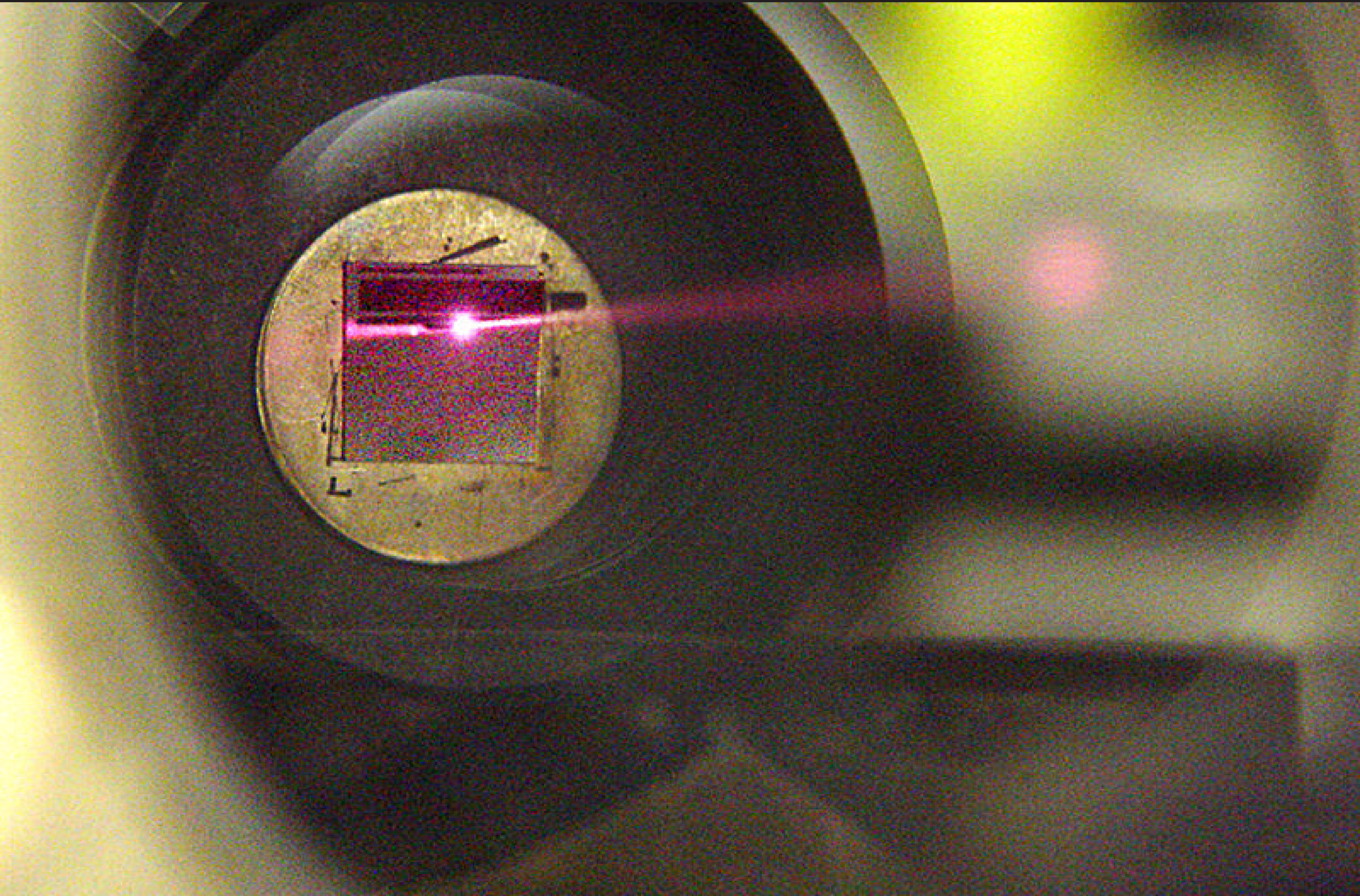
- transparent materials
- bulk micromachining
- **non transparent materials**
- optical hyperdoping

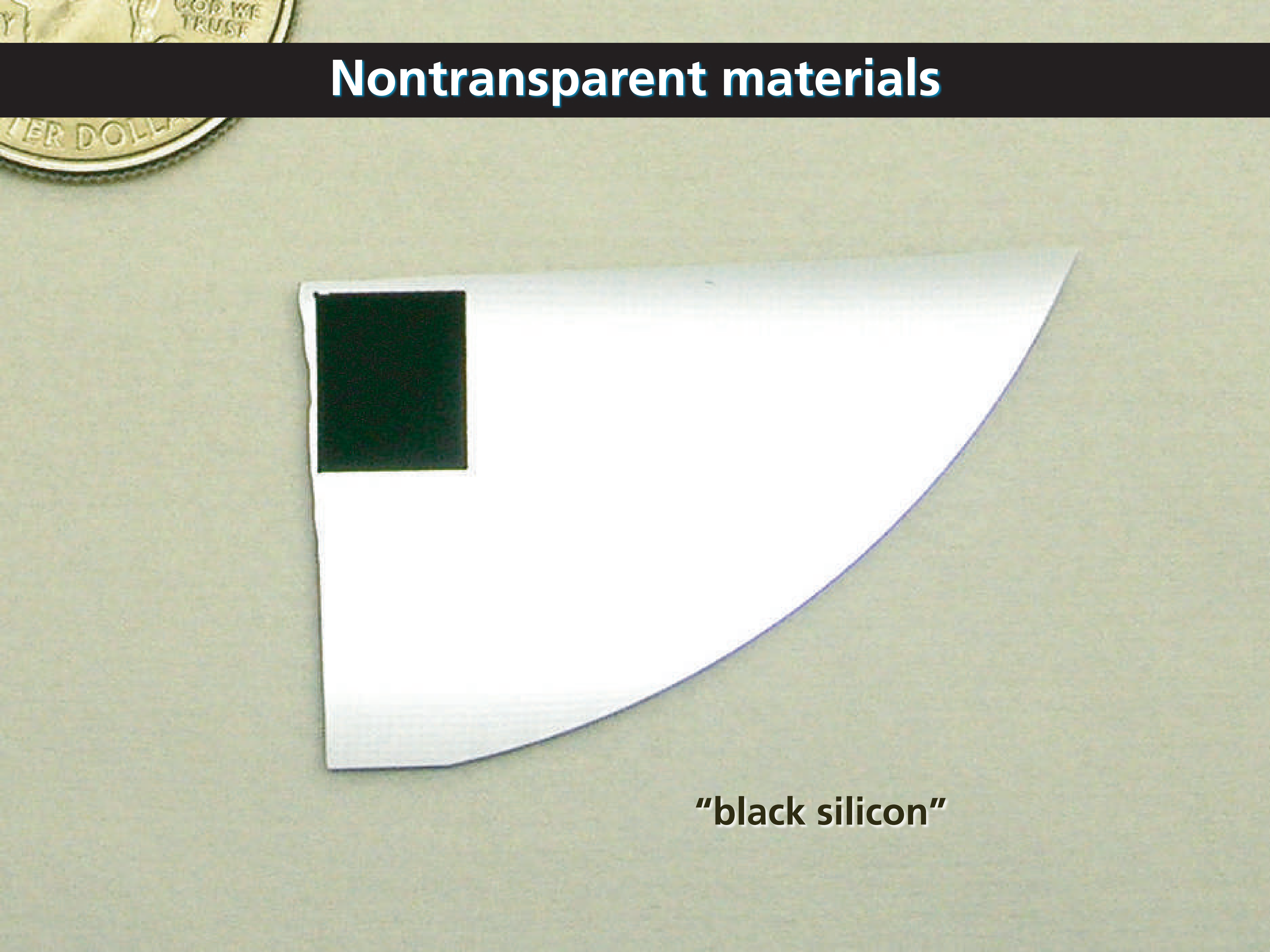
Nontransparent materials



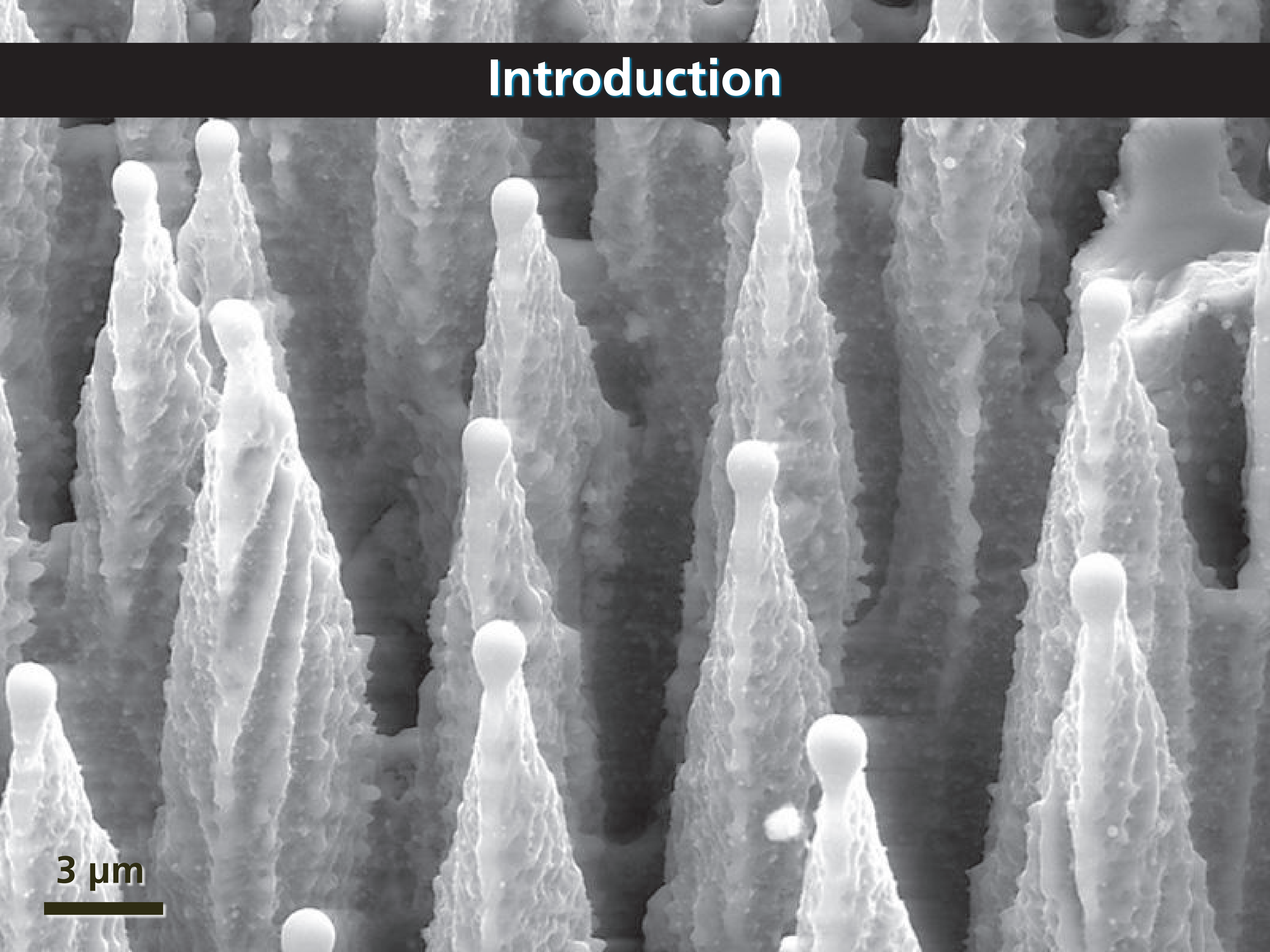
irradiate with 100-fs 10 kJ/m^2 pulses

Nontransparent materials



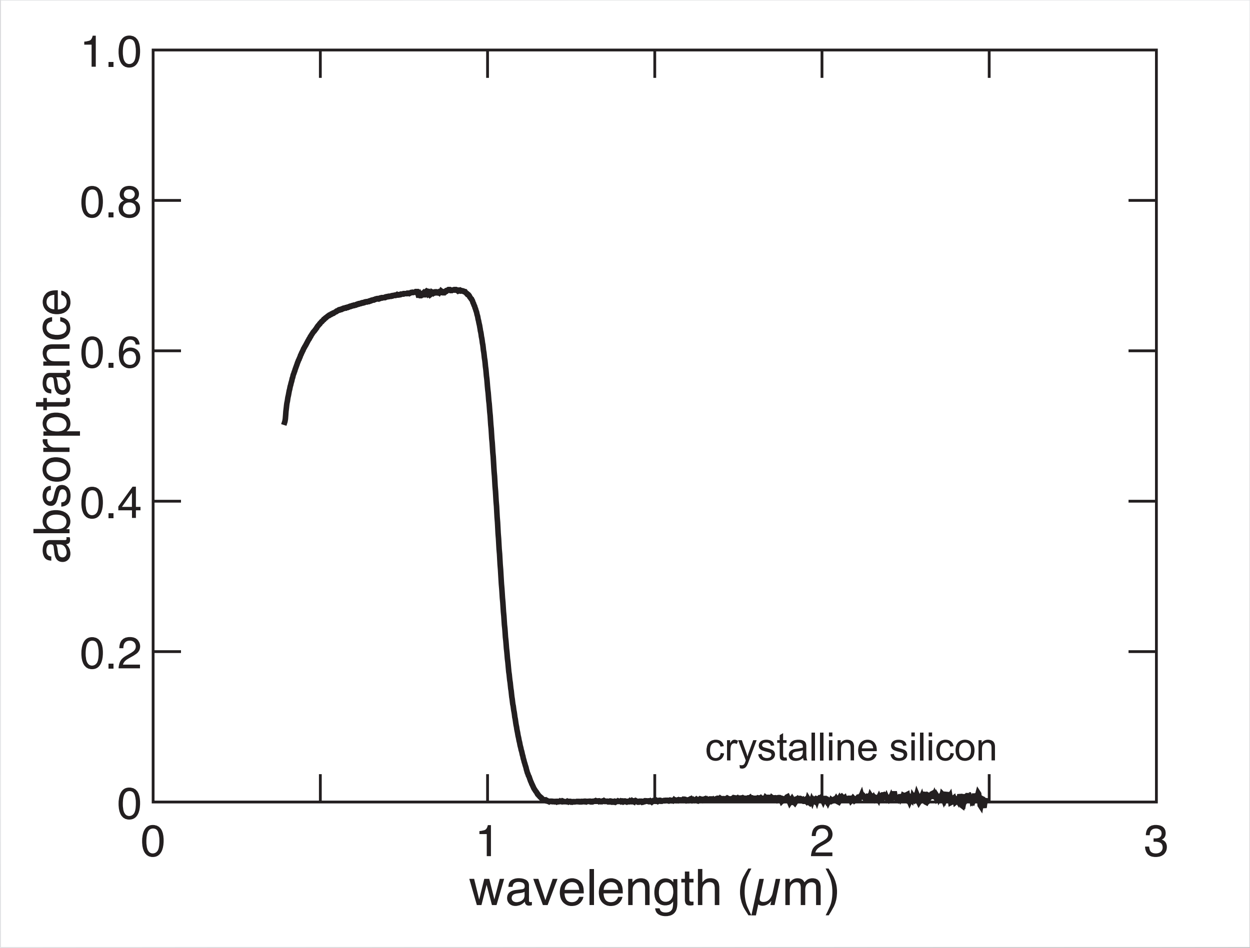

Nontransparent materials
“black silicon”

Introduction



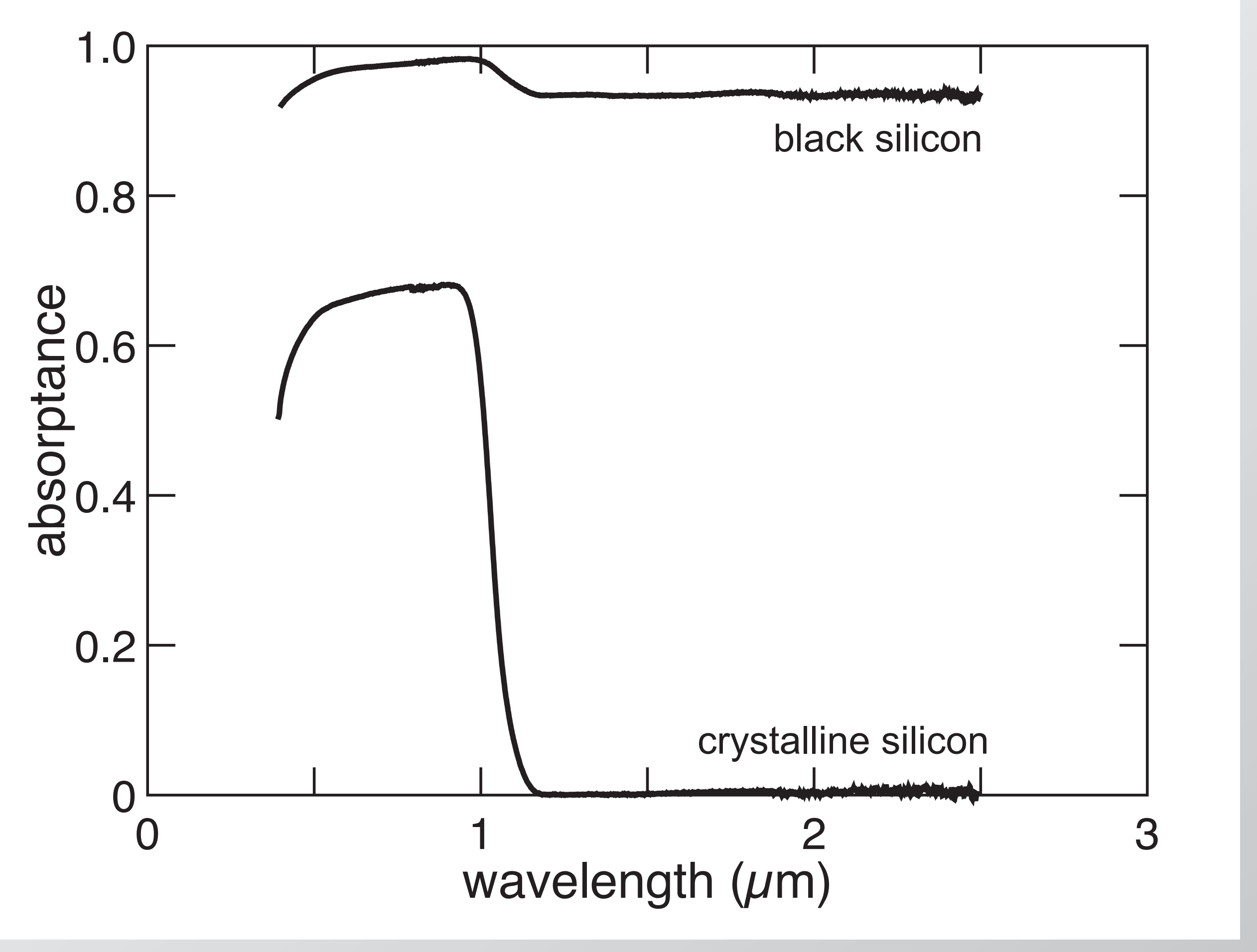
Introduction

absorptance (1 – R_{int} – T_{int})

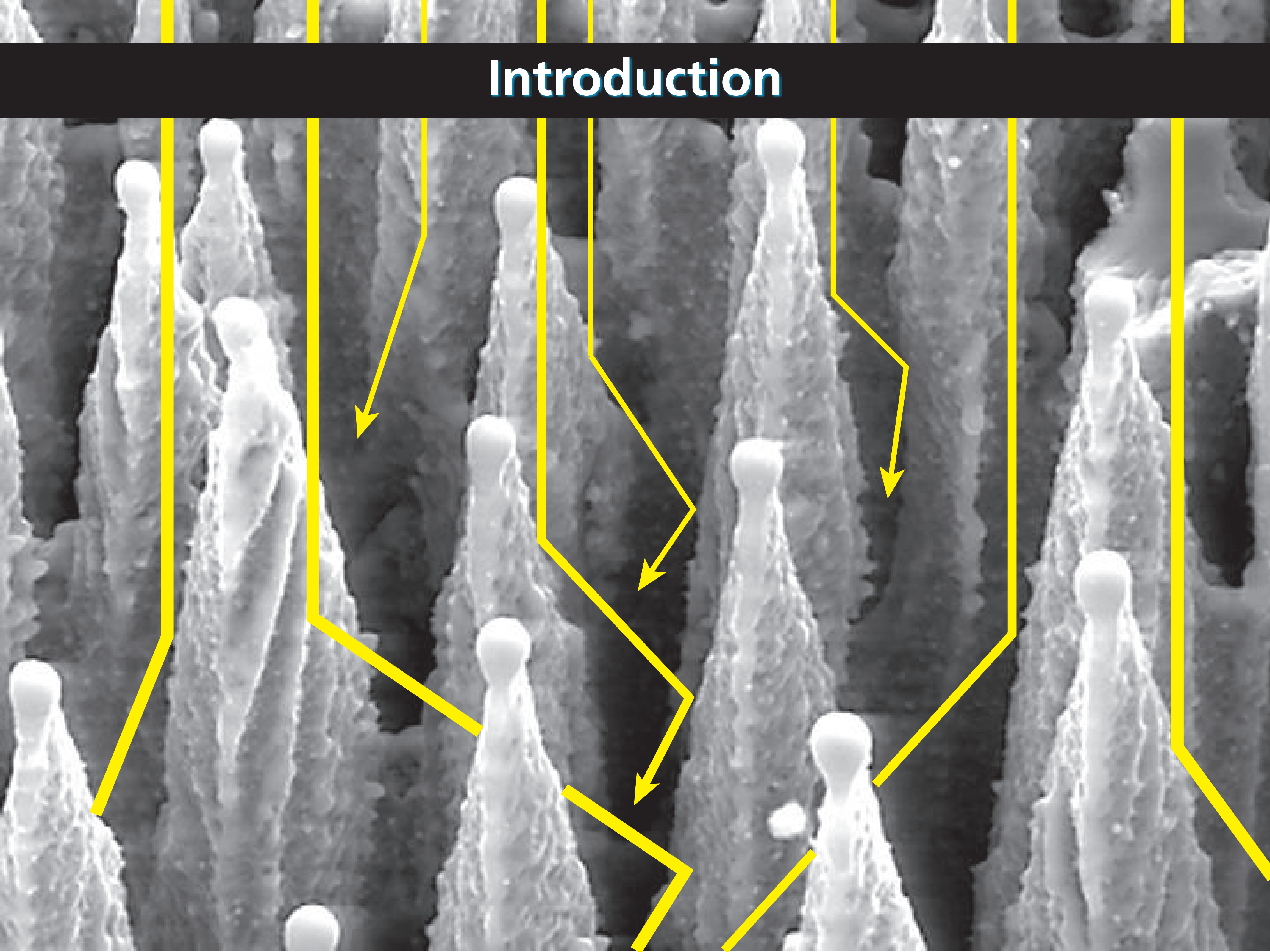


Nontransparent materials

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

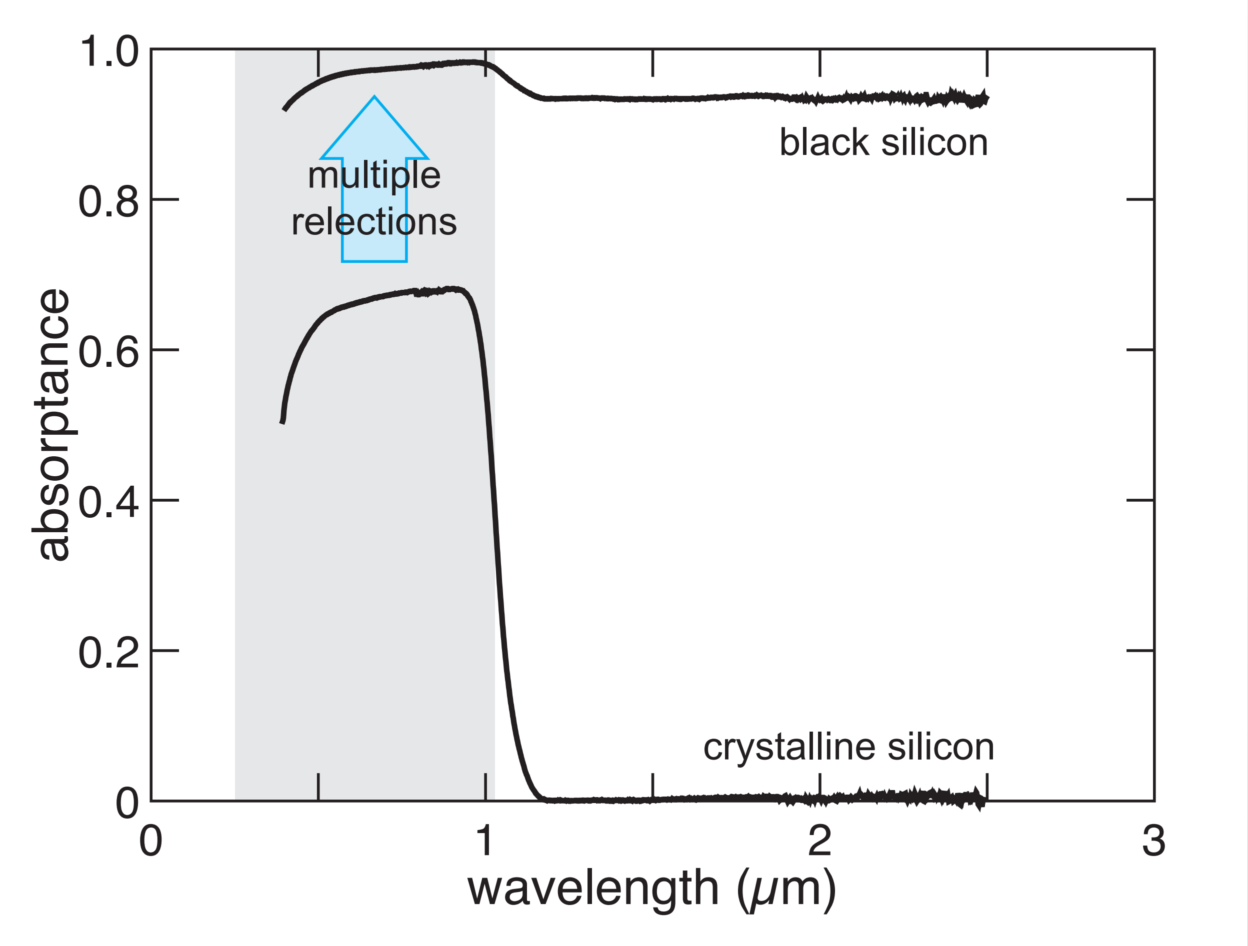


Introduction



Nontransparent materials

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



Nontransparent materials

band structure changes: defects and/or impurities

Nontransparent materials

substrate/dopant combinations

dopants:

N	O	F
P	S	Cl
	Se	
Sb	Te	

Nontransparent materials

substrate/dopant combinations

dopants:

N	O	F
P	S	Cl
	Se	
Sb	Te	

substrates:

Si Ge ZnO InP GaAs

Ti Ag Al Cu Pd Rh Ta Pt

Nontransparent materials

focus on chalcogen-doped silicon

dopants:

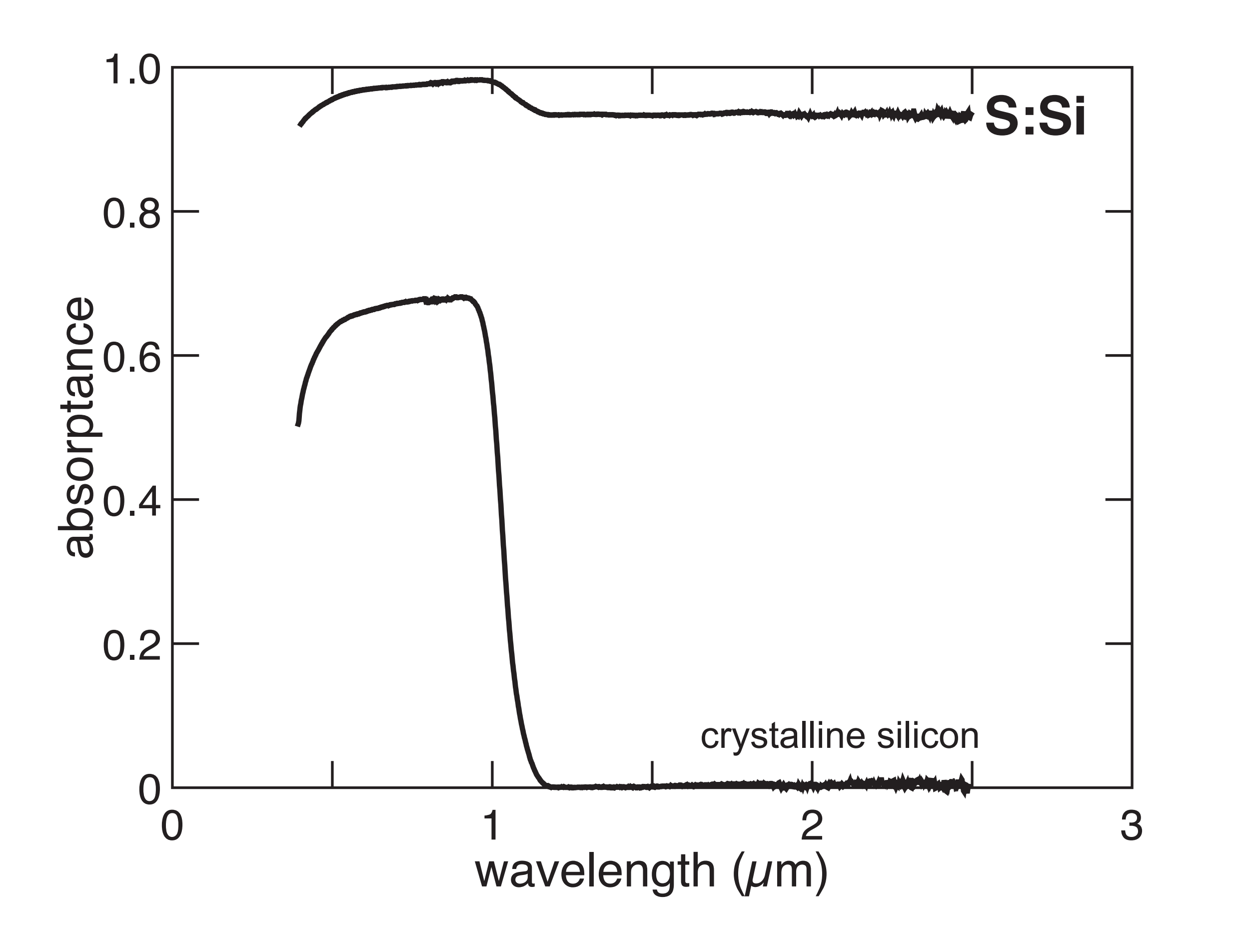
N	O	F
P	S	Cl
	Se	
Sb	Te	

substrates:

Si	Ge	ZnO	InP	GaAs			
Ti	Ag	Al	Cu	Pd	Rh	Ta	Pt

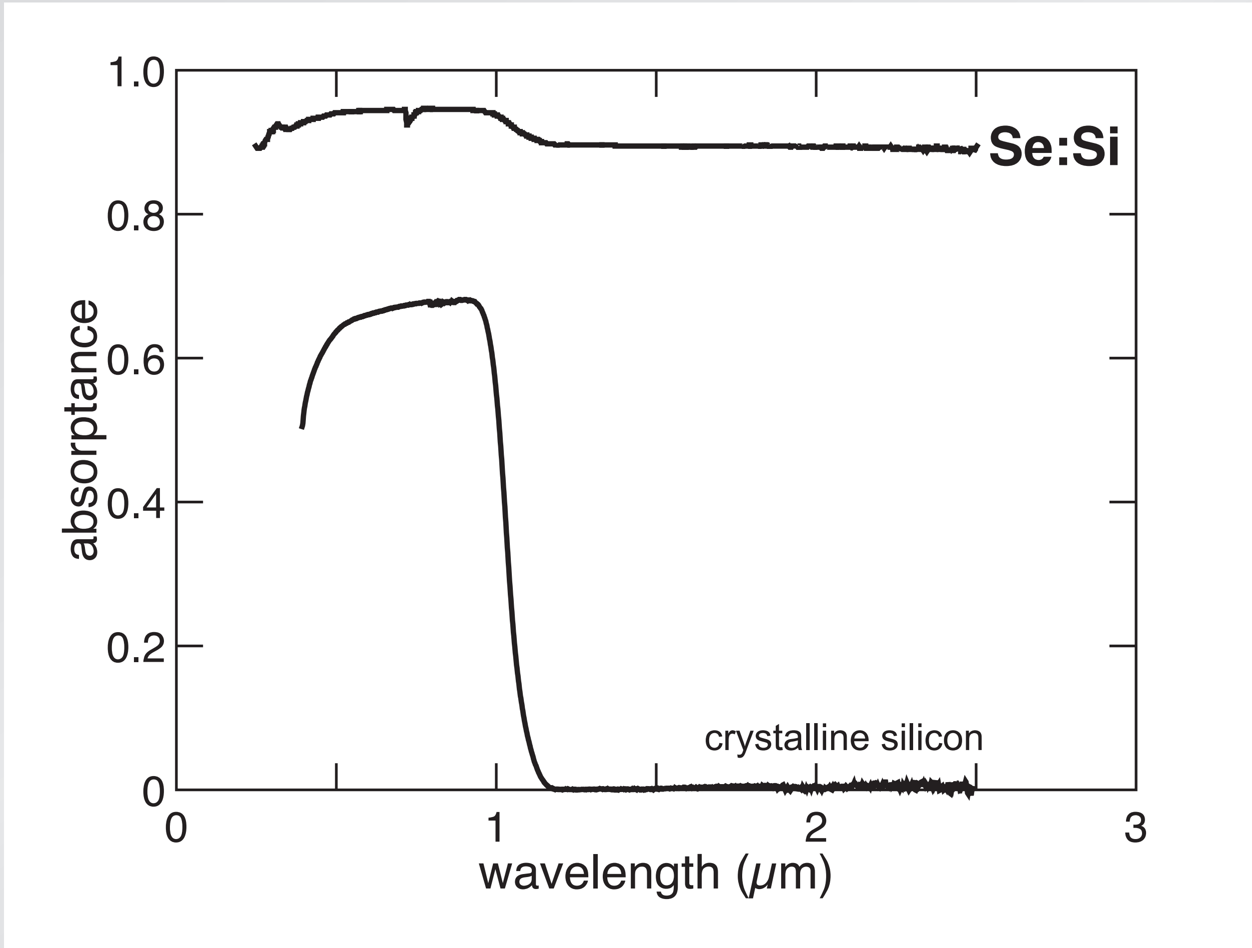
Nontransparent materials

focus on chalcogen-doped silicon



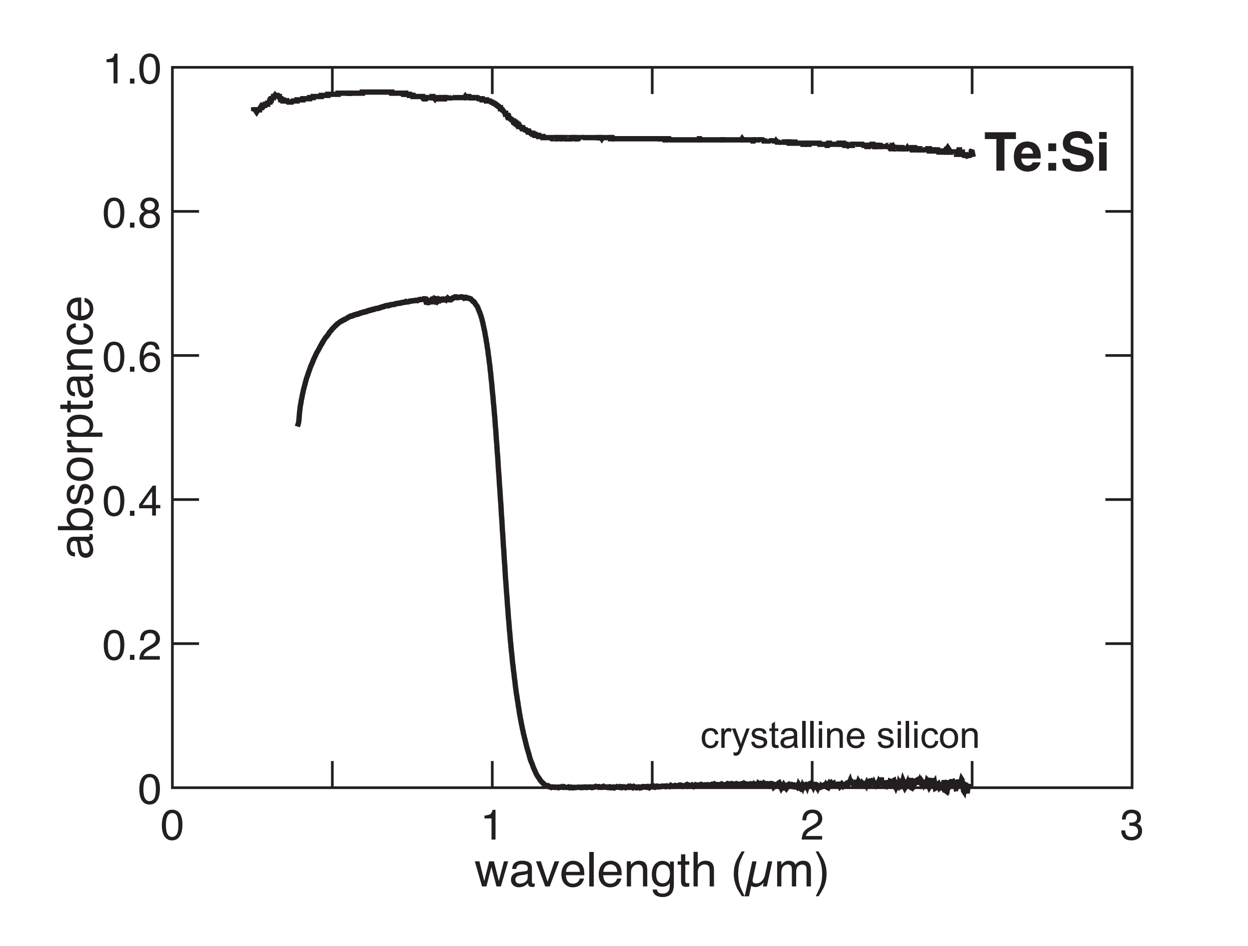
Nontransparent materials

focus on chalcogen-doped silicon

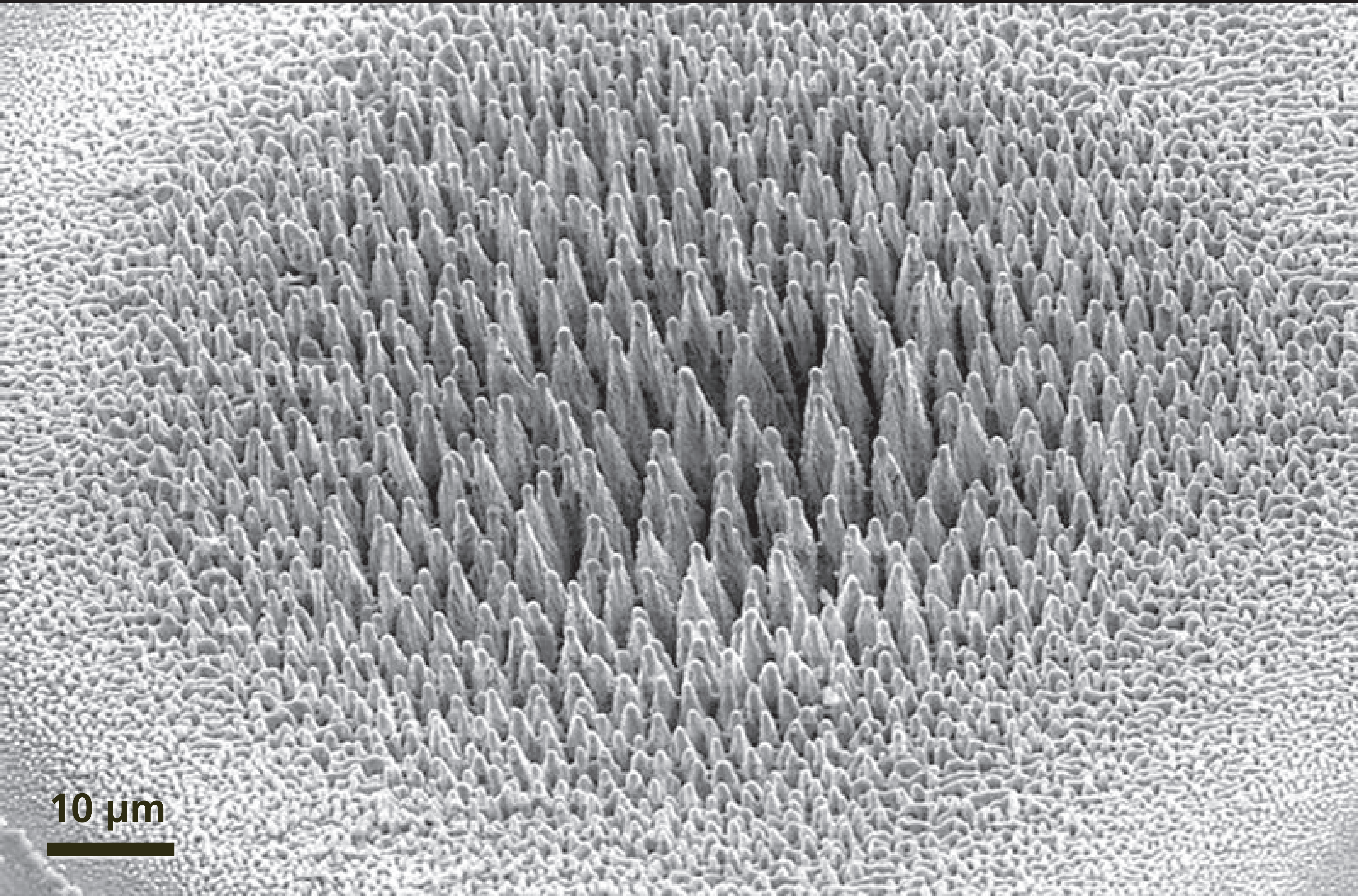


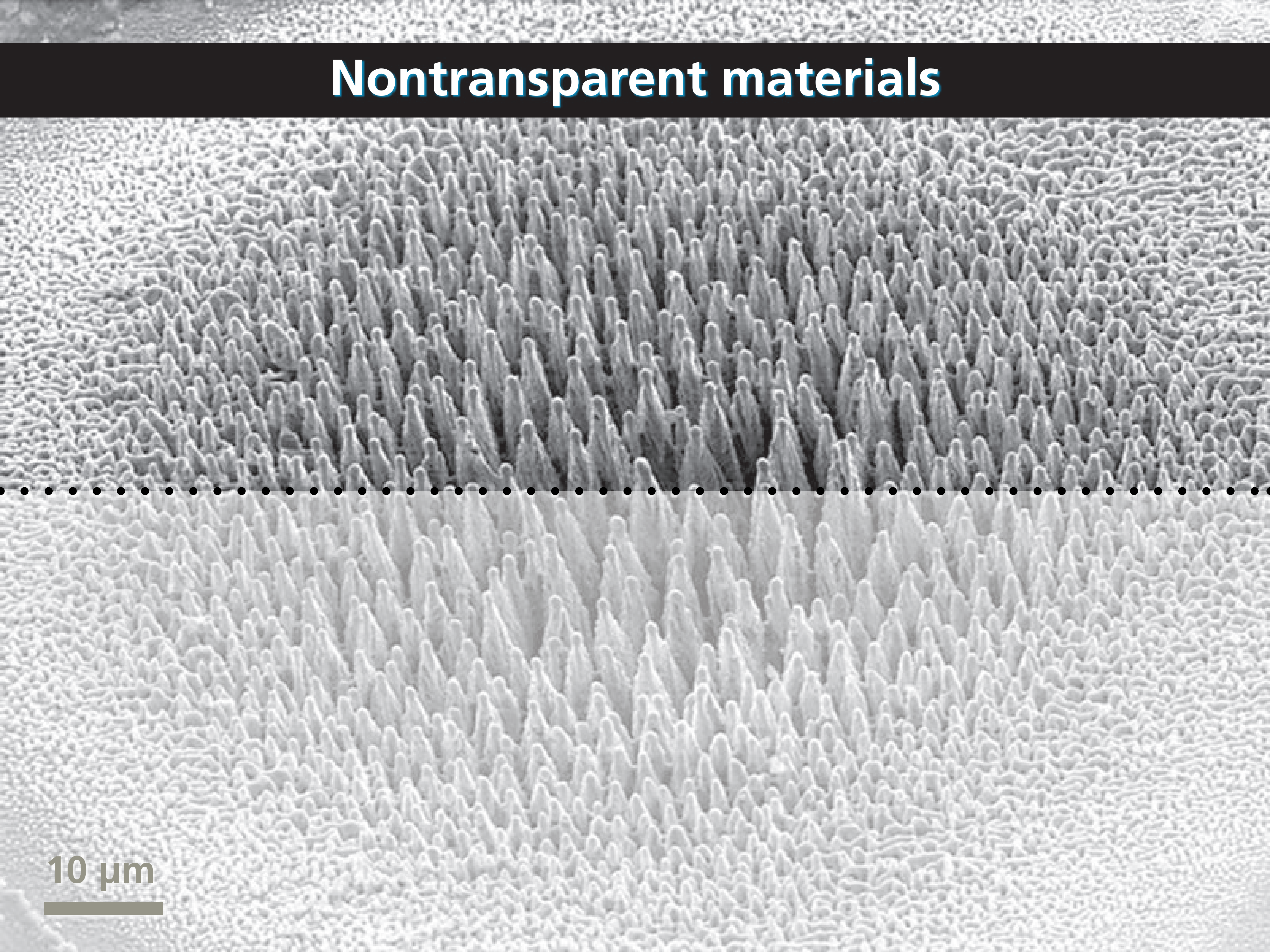
Nontransparent materials

focus on chalcogen-doped silicon

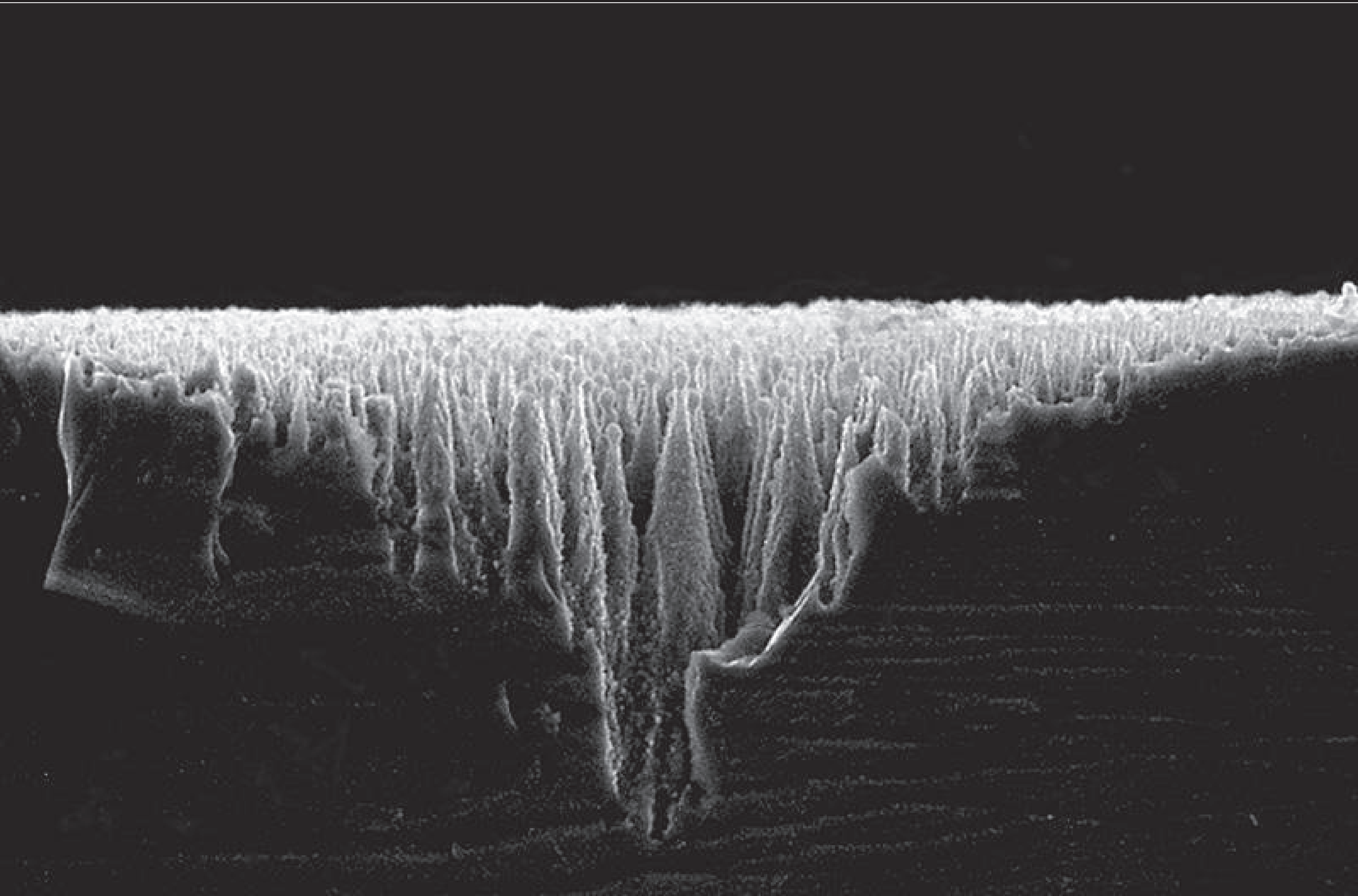


Nontransparent materials

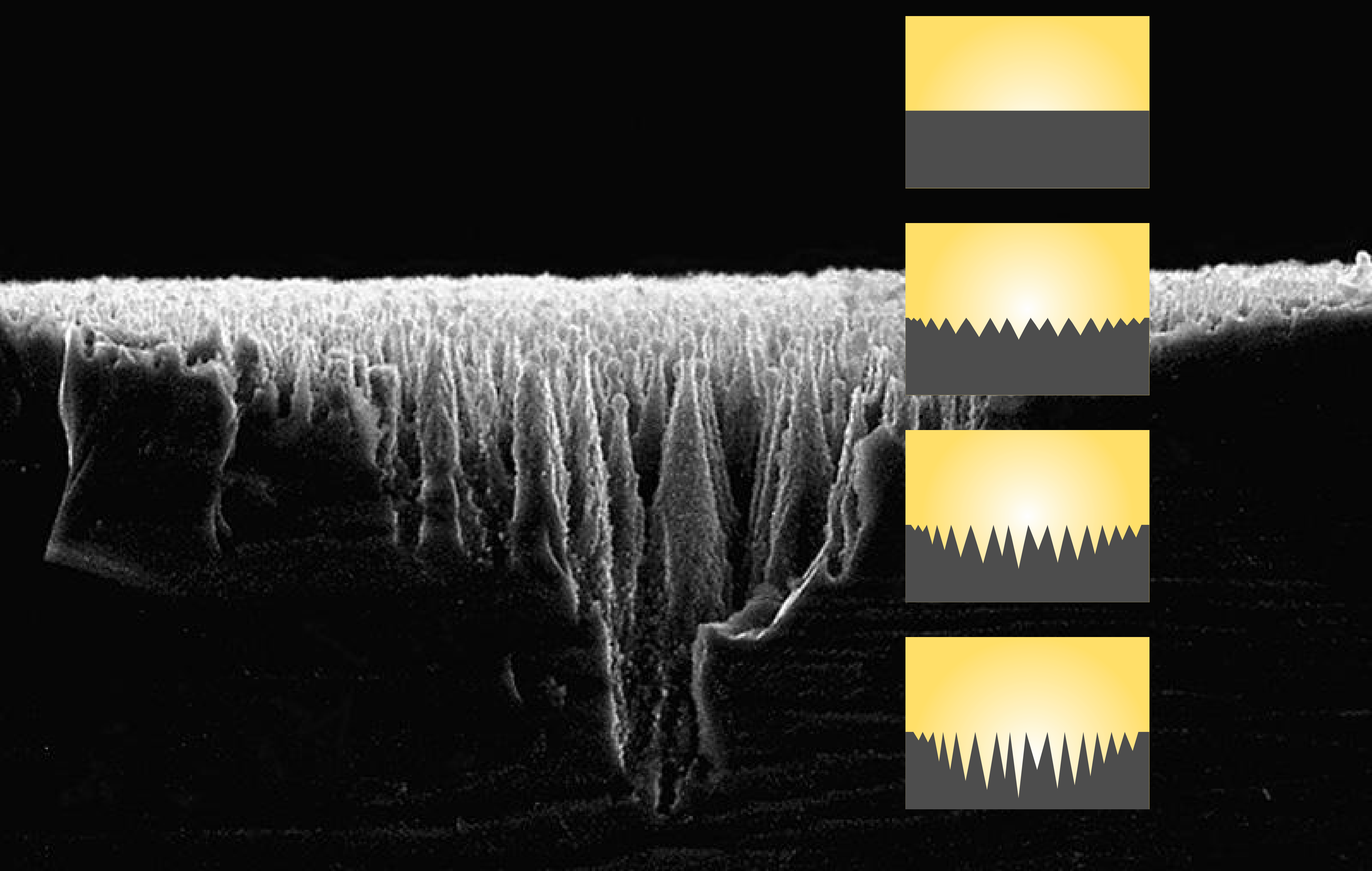



Nontransparent materials
10 µm

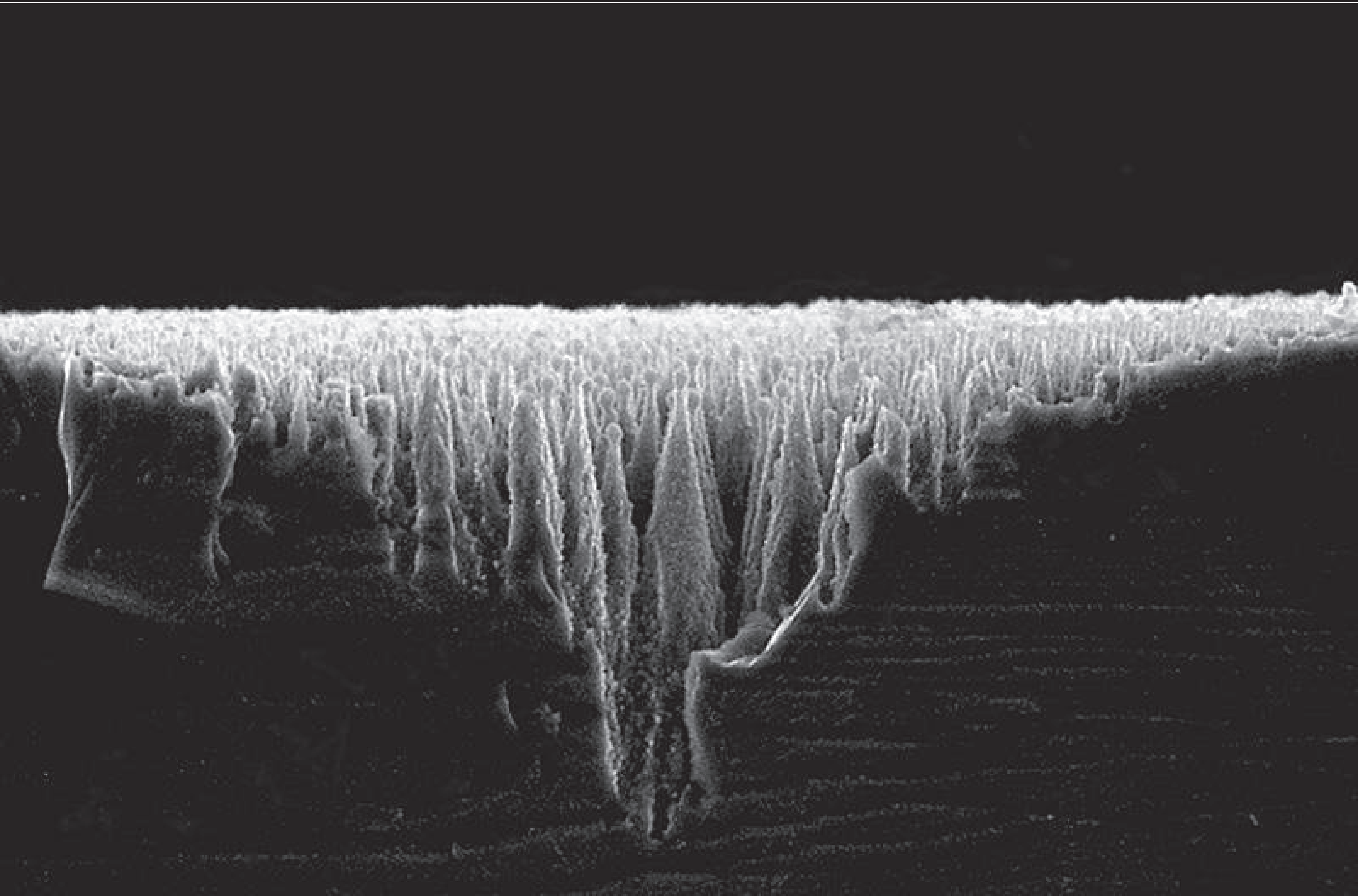
Nontransparent materials



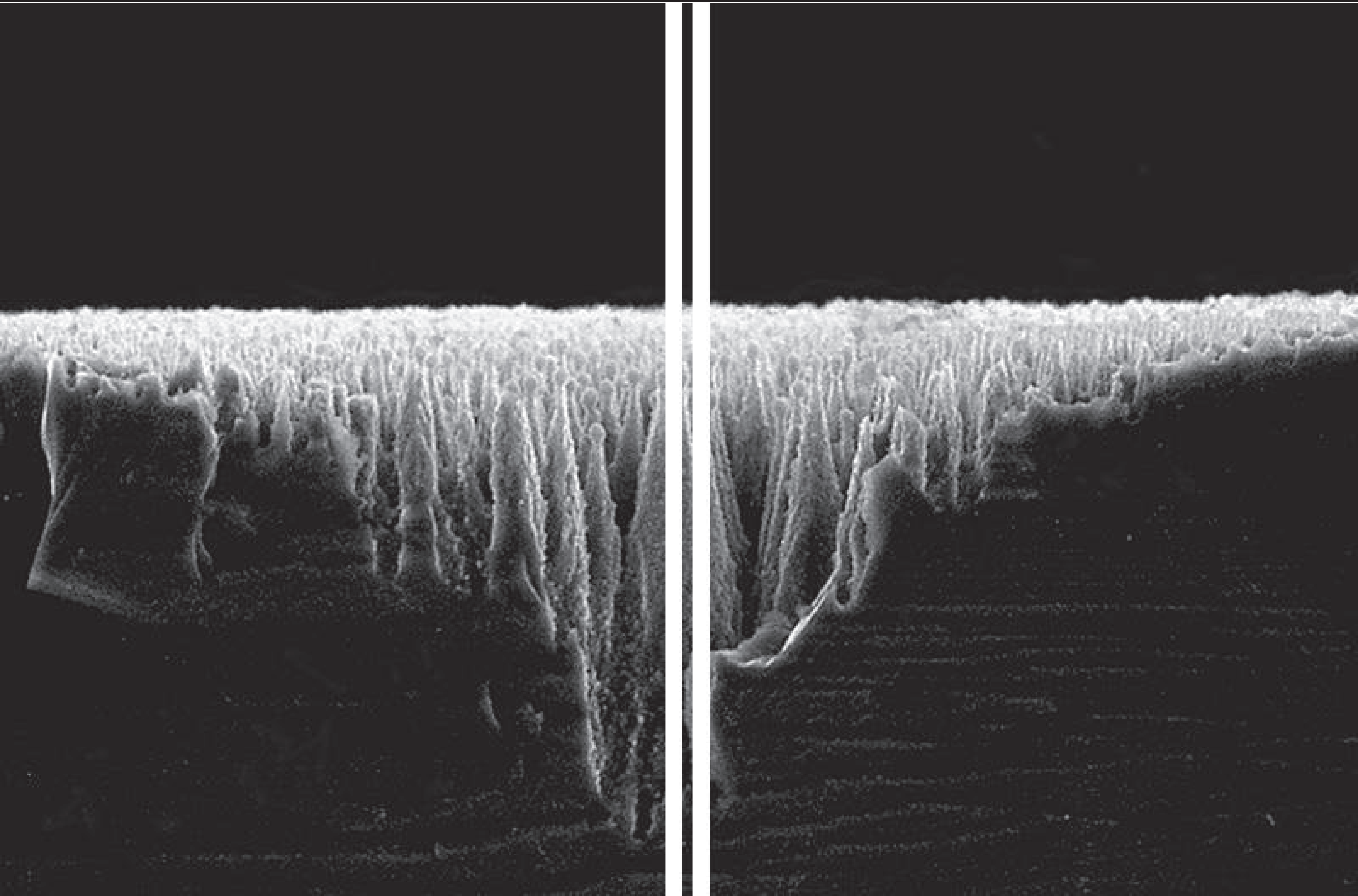
Nontransparent materials



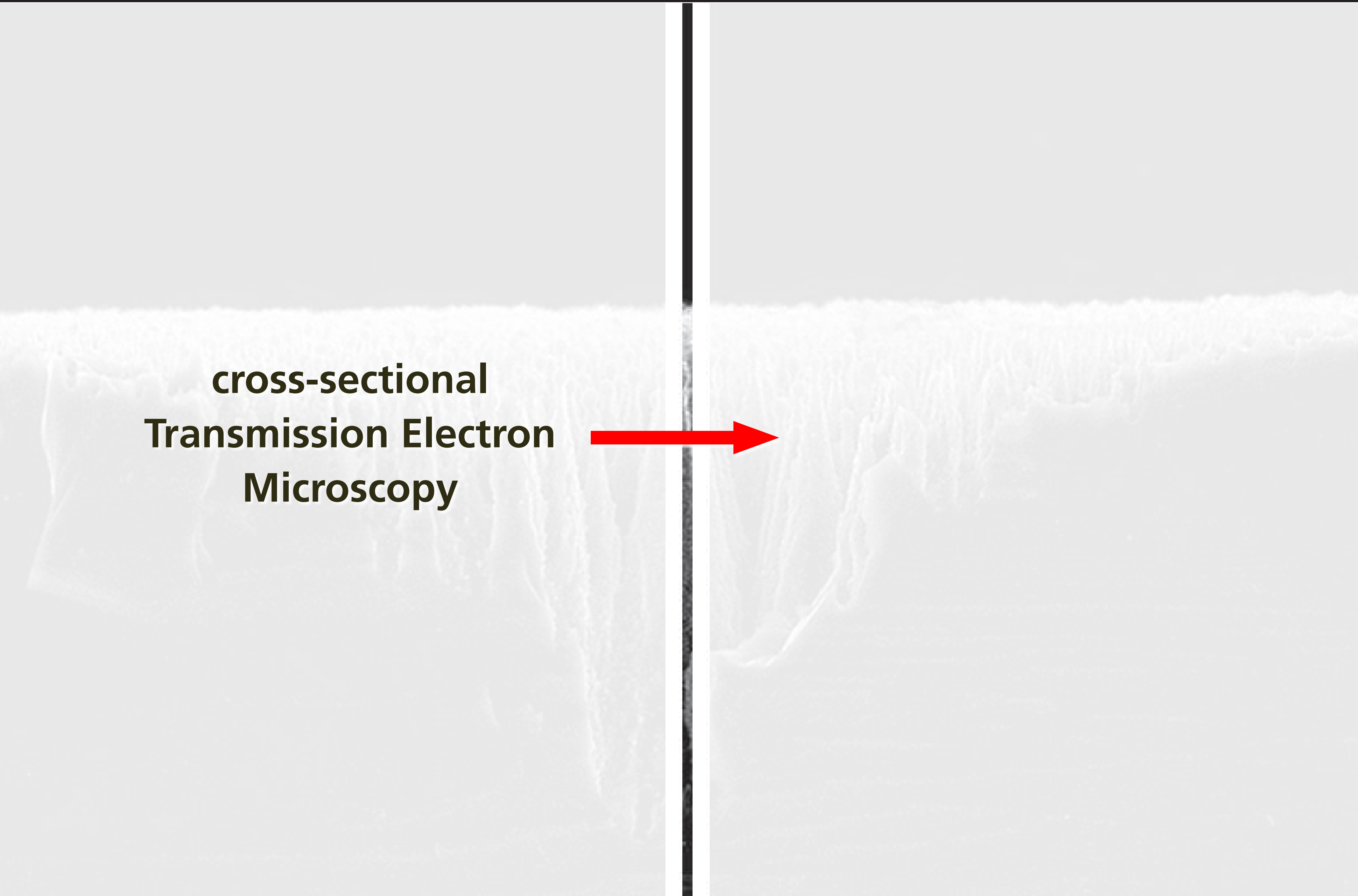
Nontransparent materials



Nontransparent materials



Nontransparent materials



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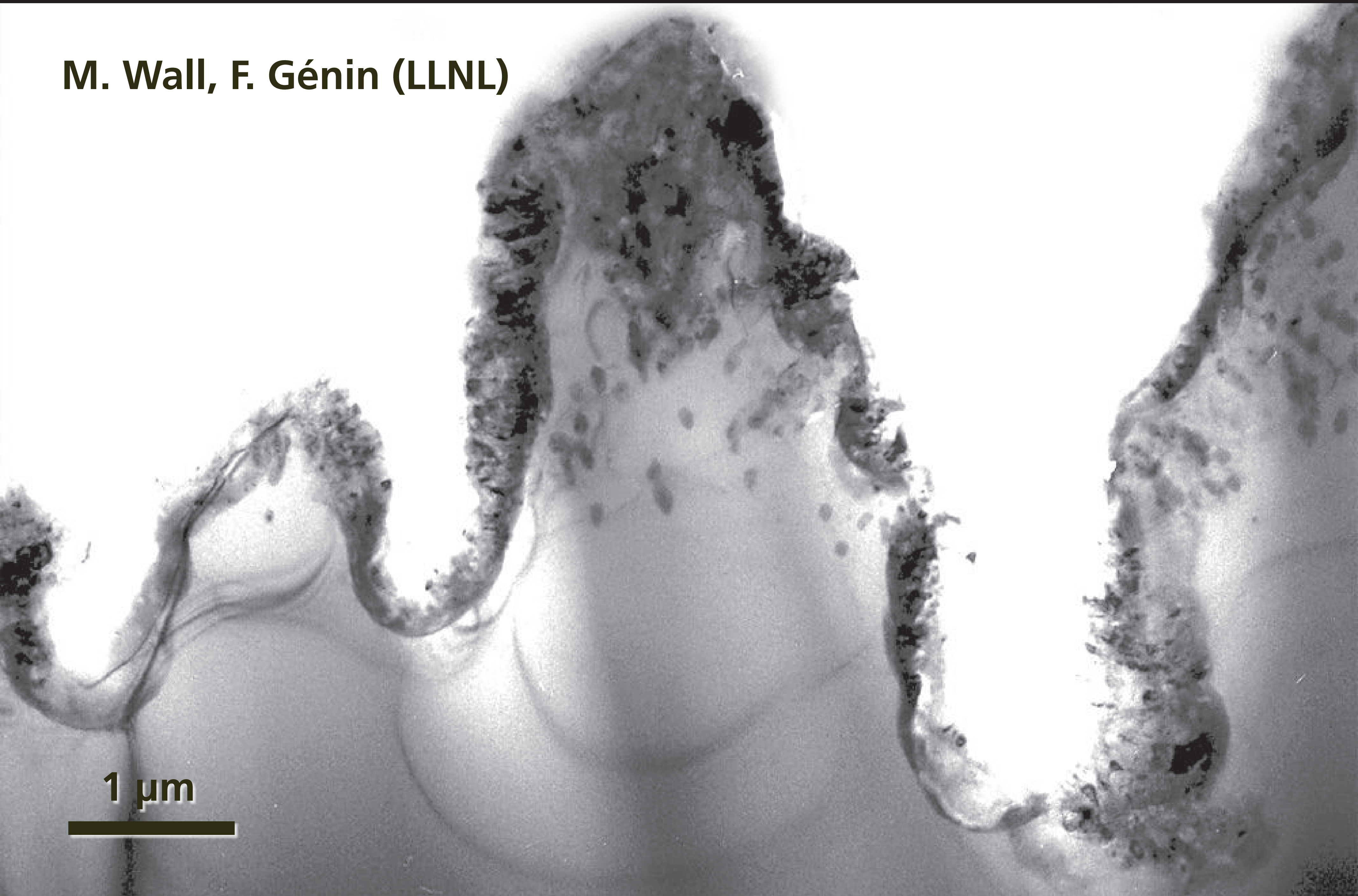

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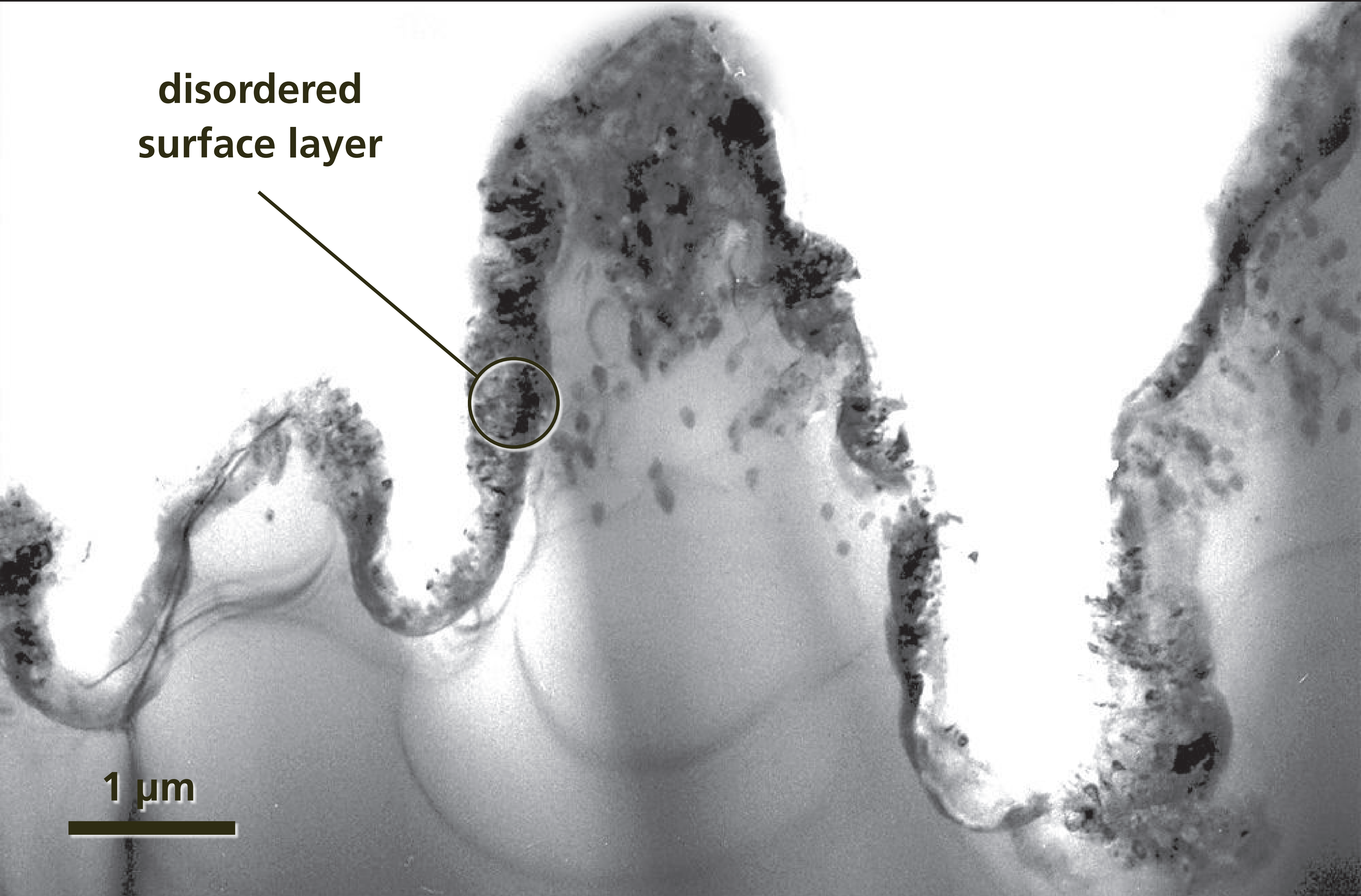

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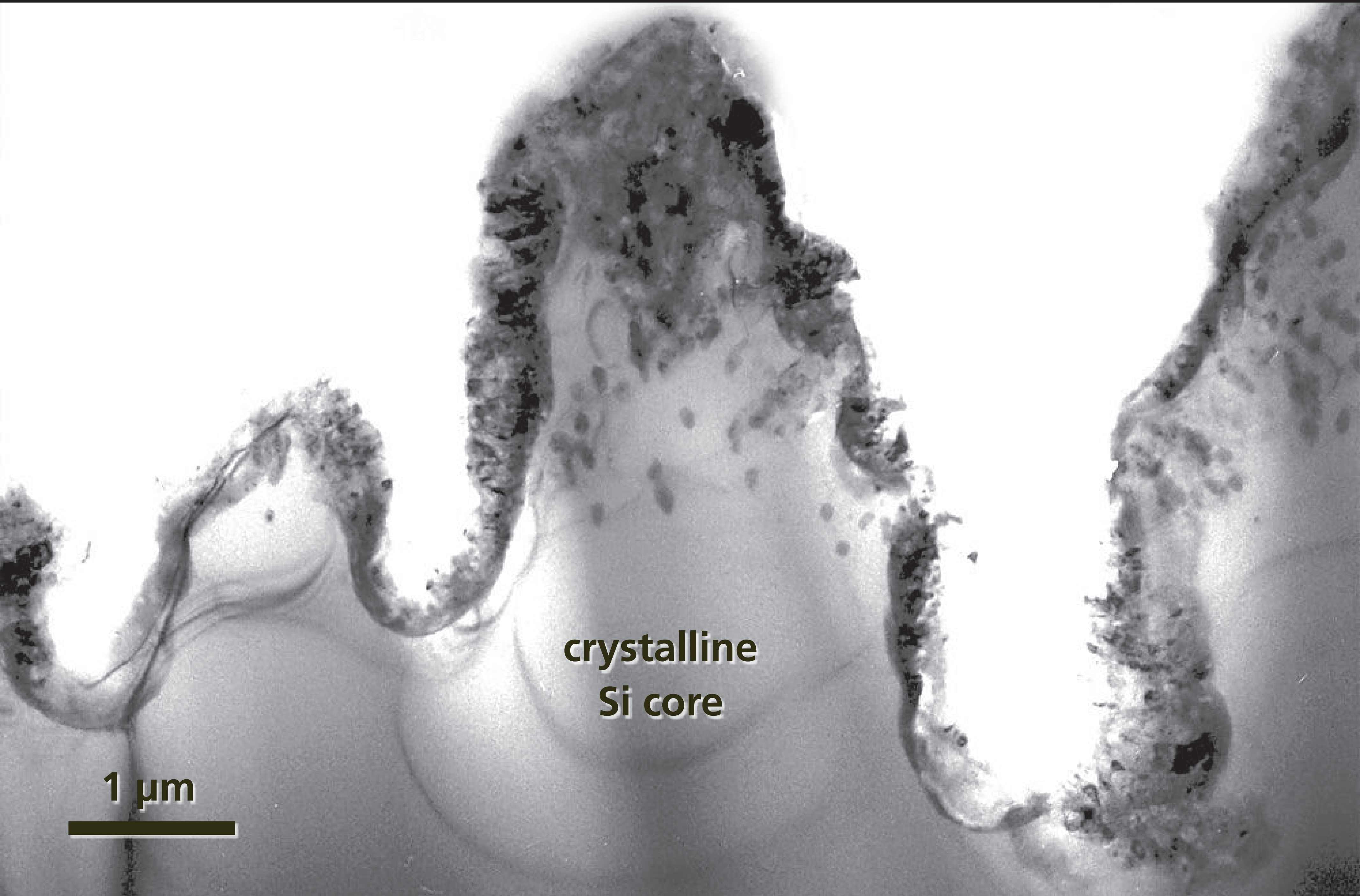

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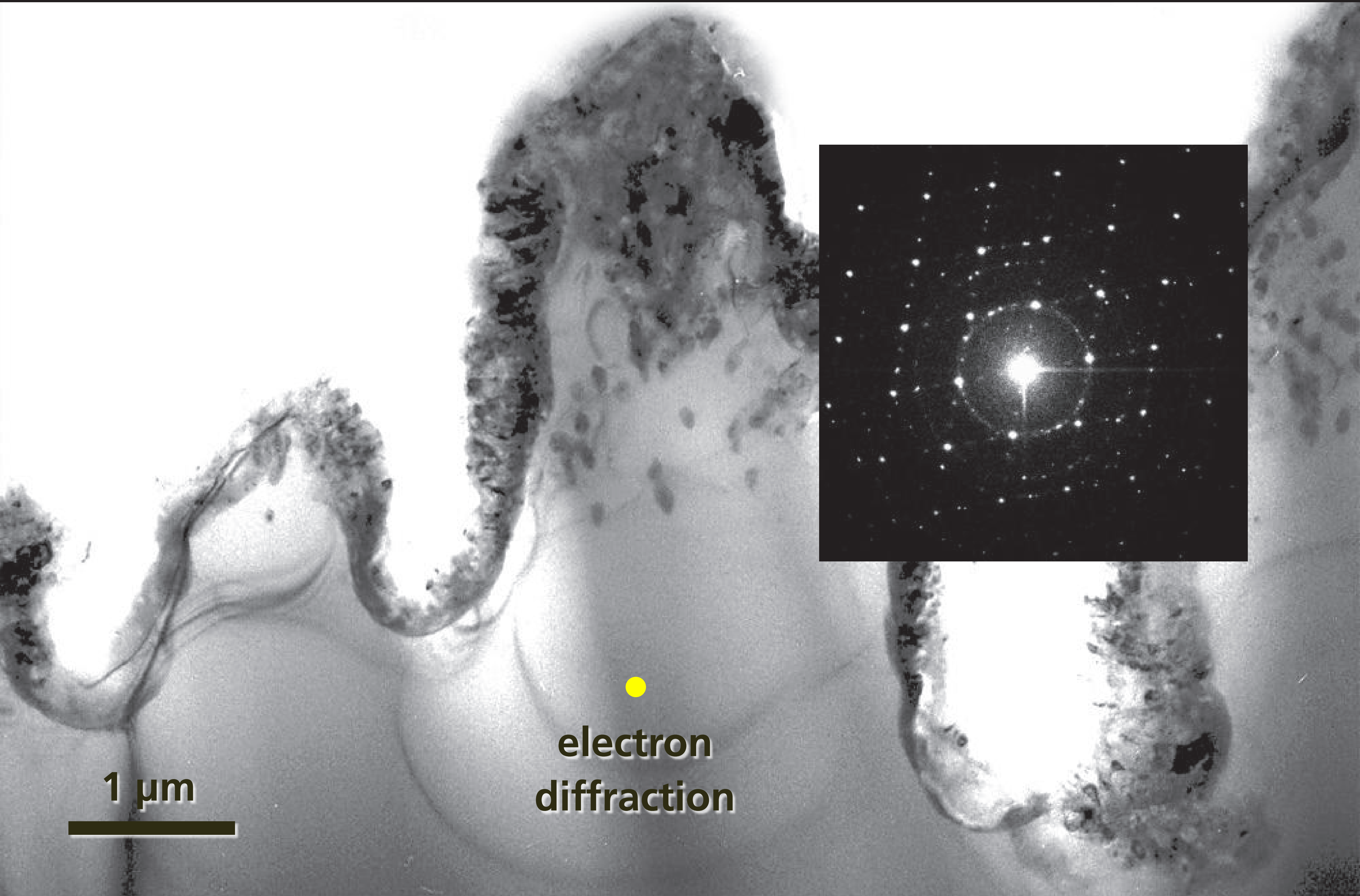
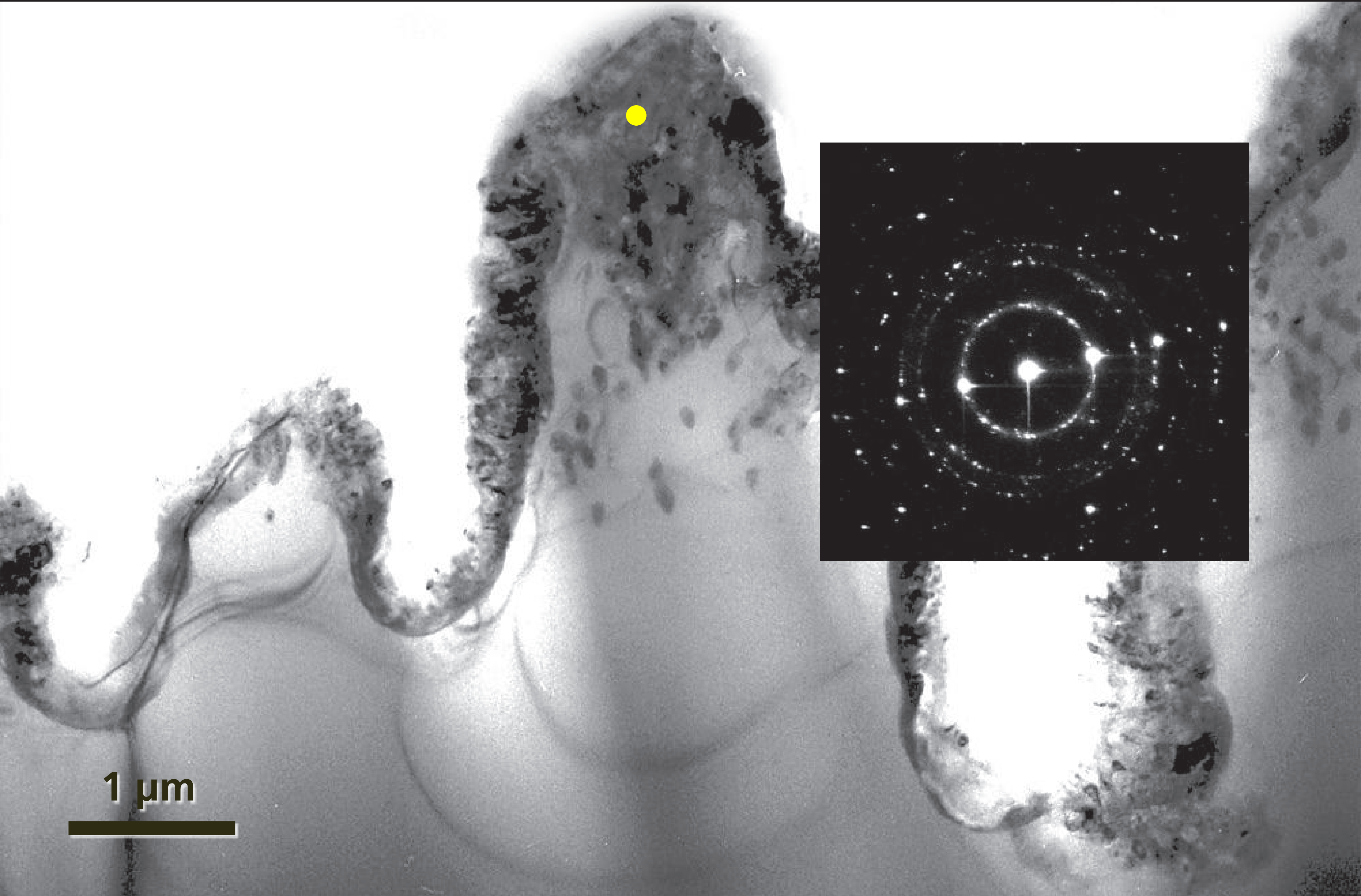
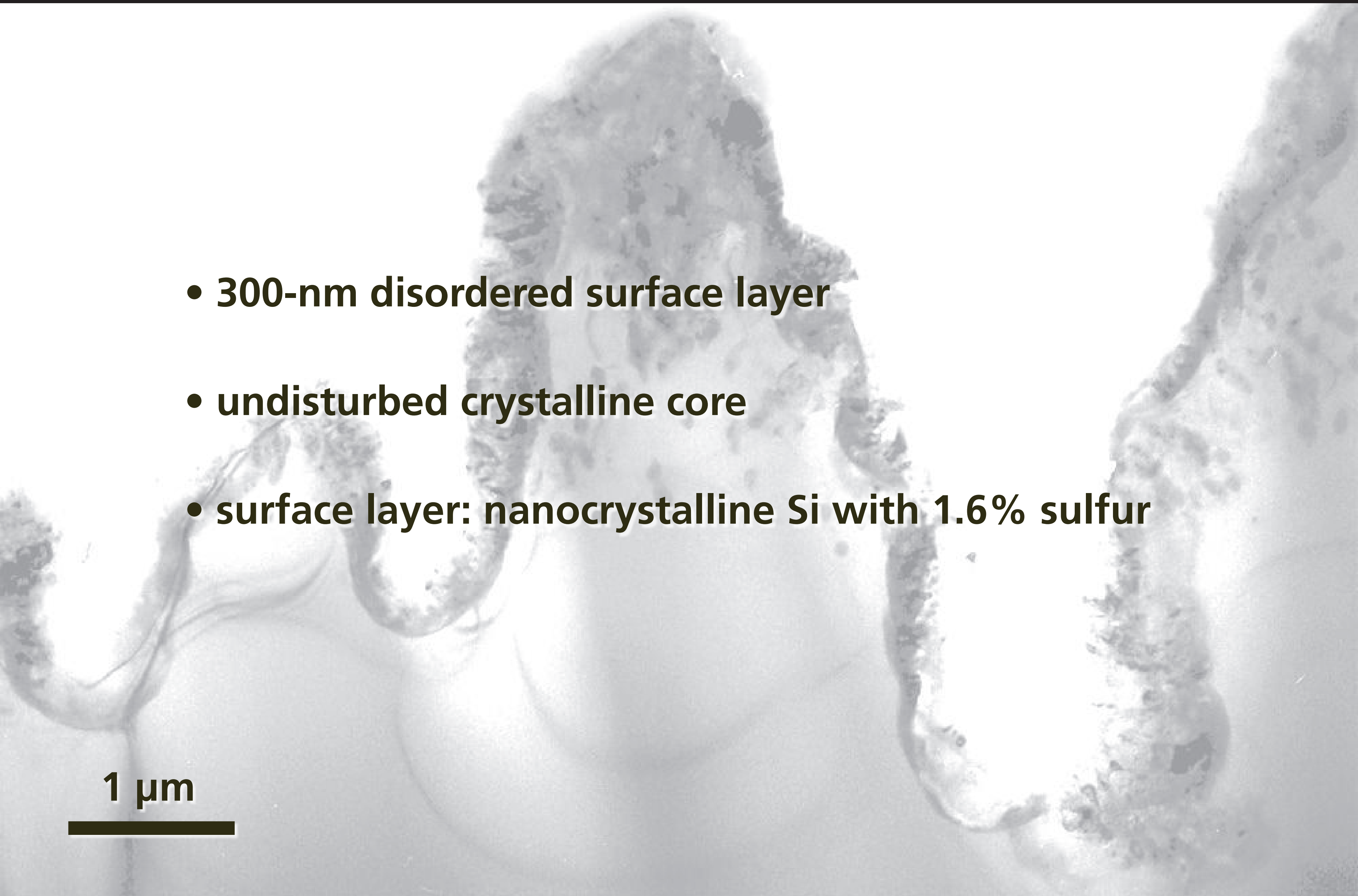


Nontransparent materials



Nontransparent materials

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

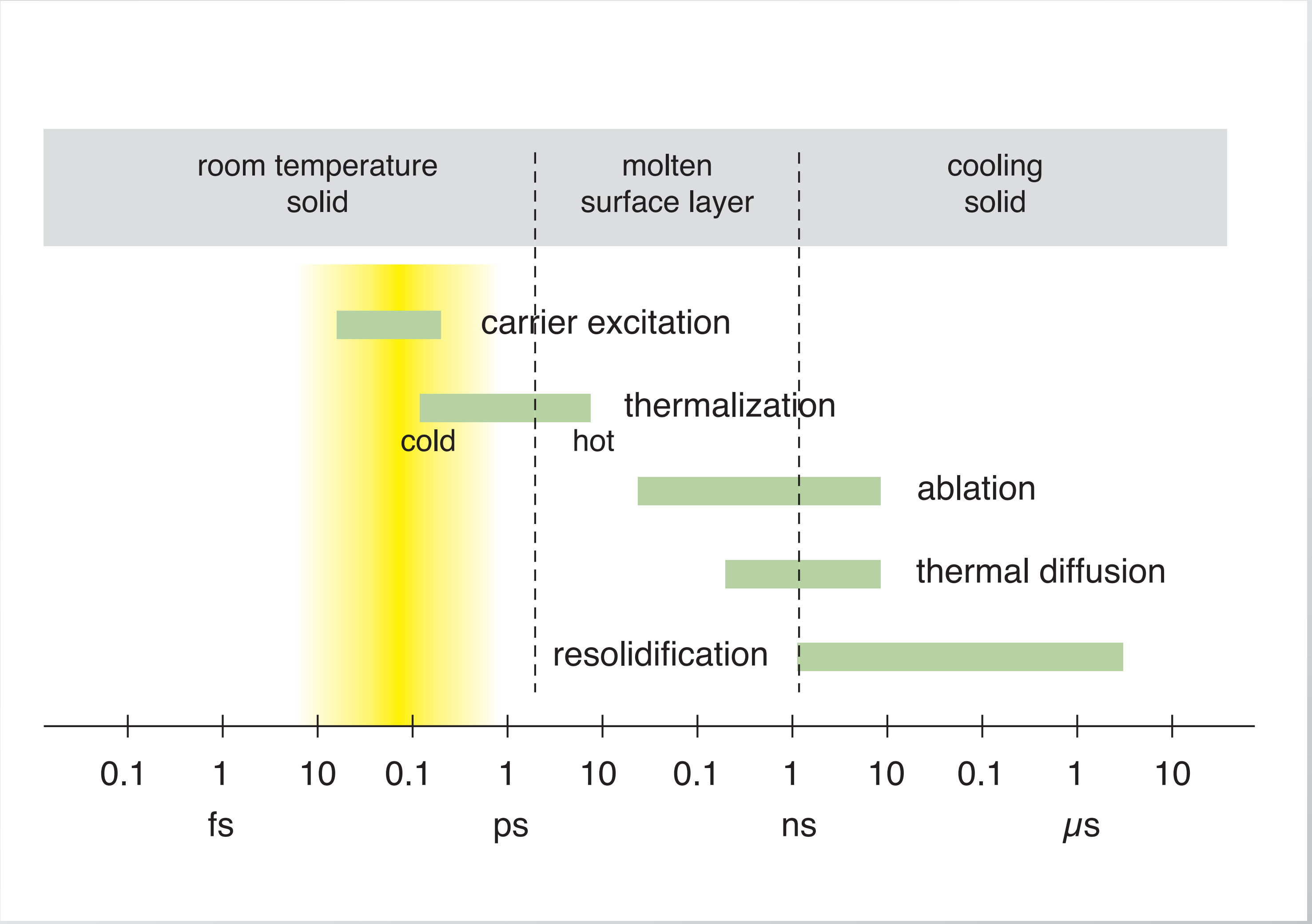


Nontransparent materials

two processes: melting and ablation

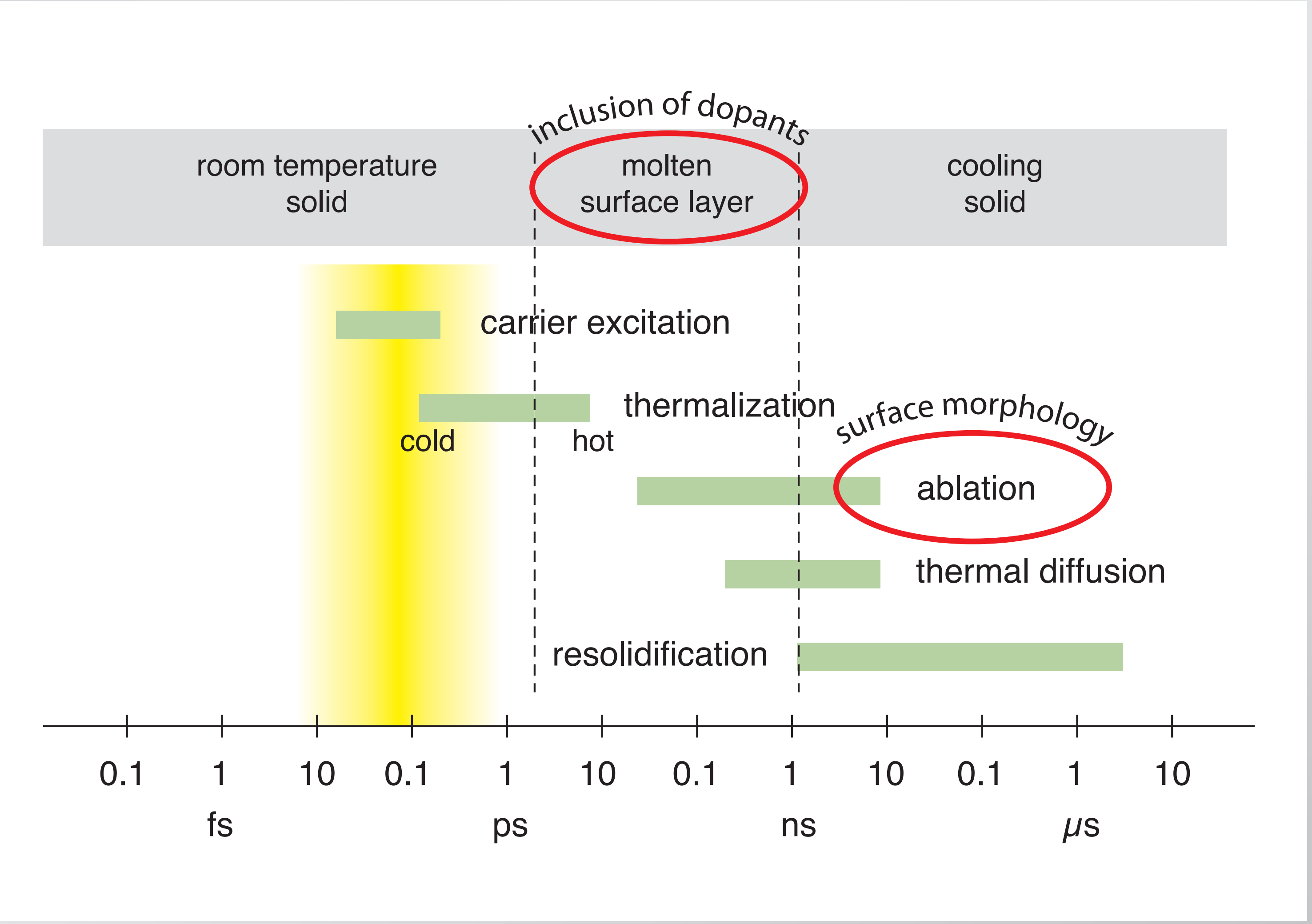
Nontransparent materials

relevant time scales



Nontransparent materials

relevant time scales



Nontransparent materials

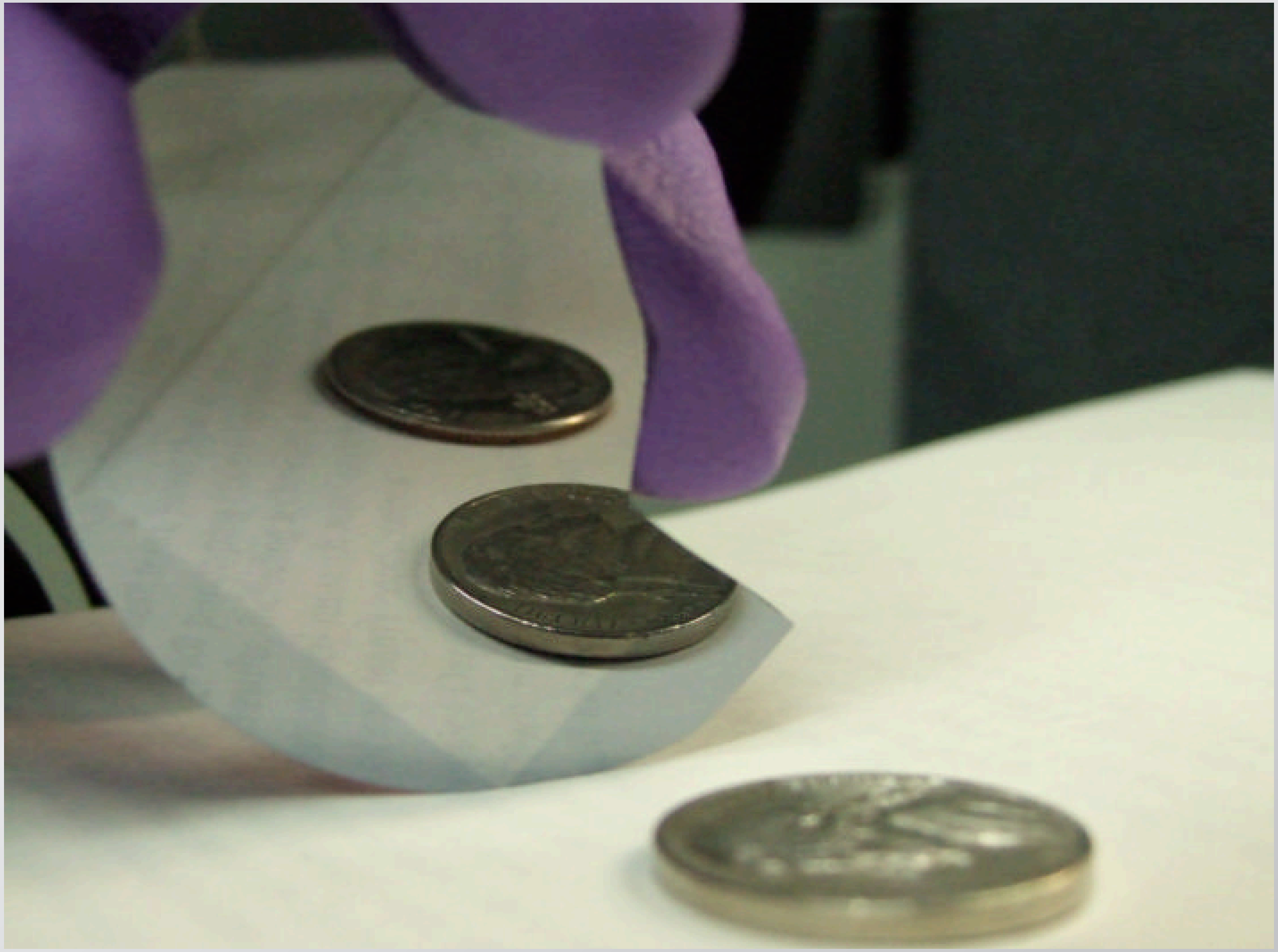
different thresholds:

melting: 1.5 kJ/m^2

ablation: 3.1 kJ/m^2

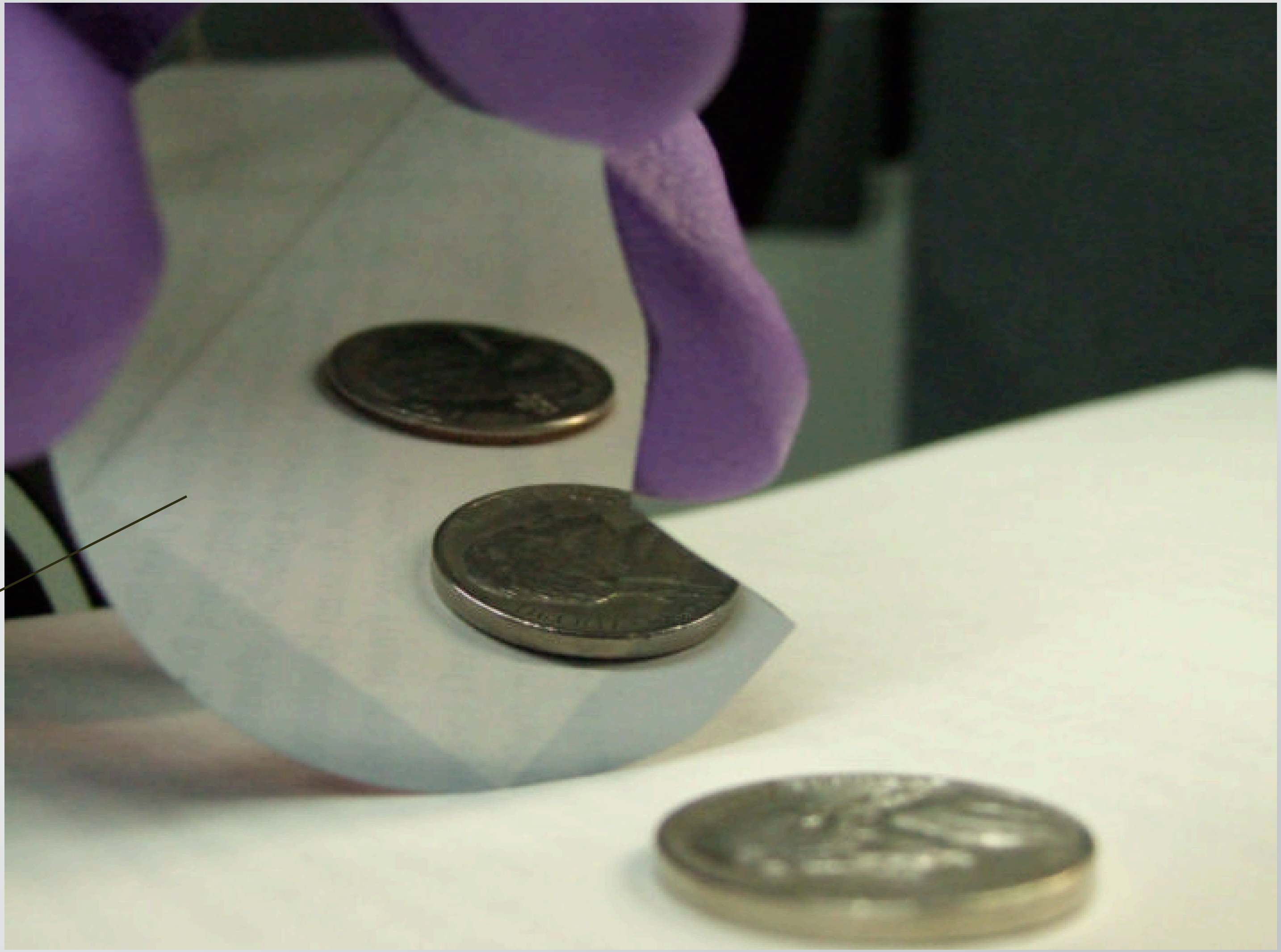
Nontransparent materials

decouple ablation from melting



Nontransparent materials

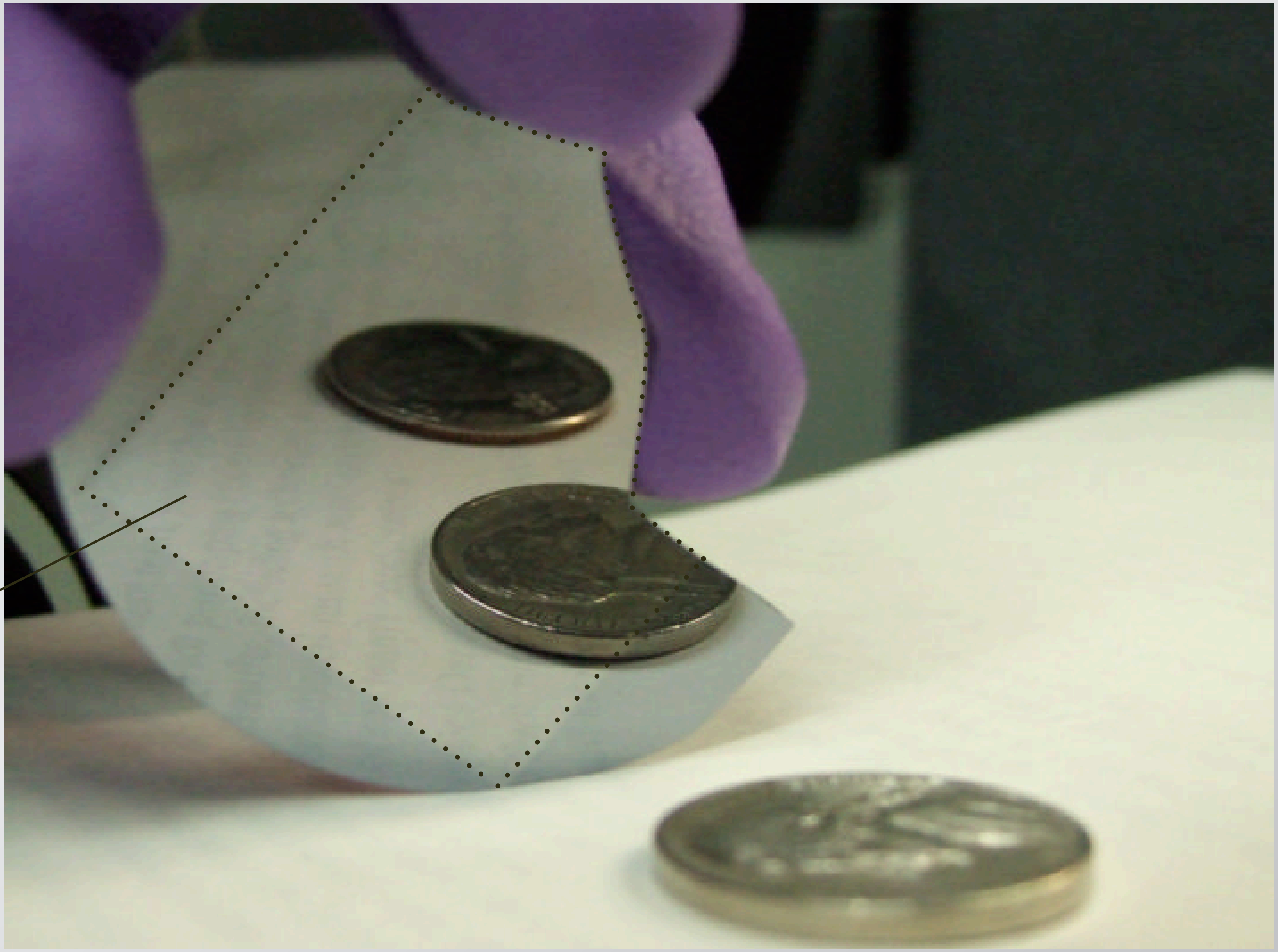
decouple ablation from melting



doped

Nontransparent materials

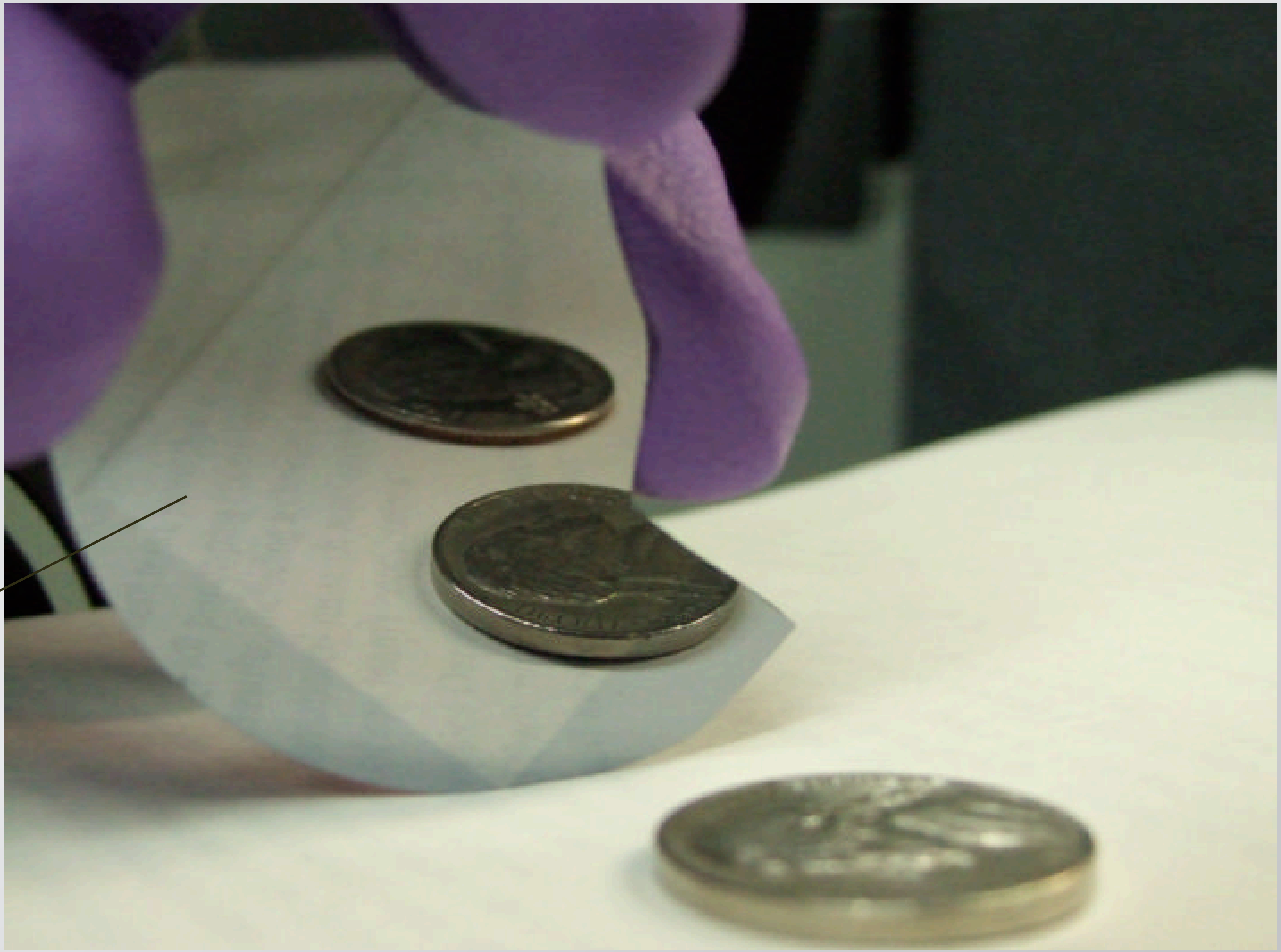
decouple ablation from melting



doped

Nontransparent materials

decouple ablation from melting

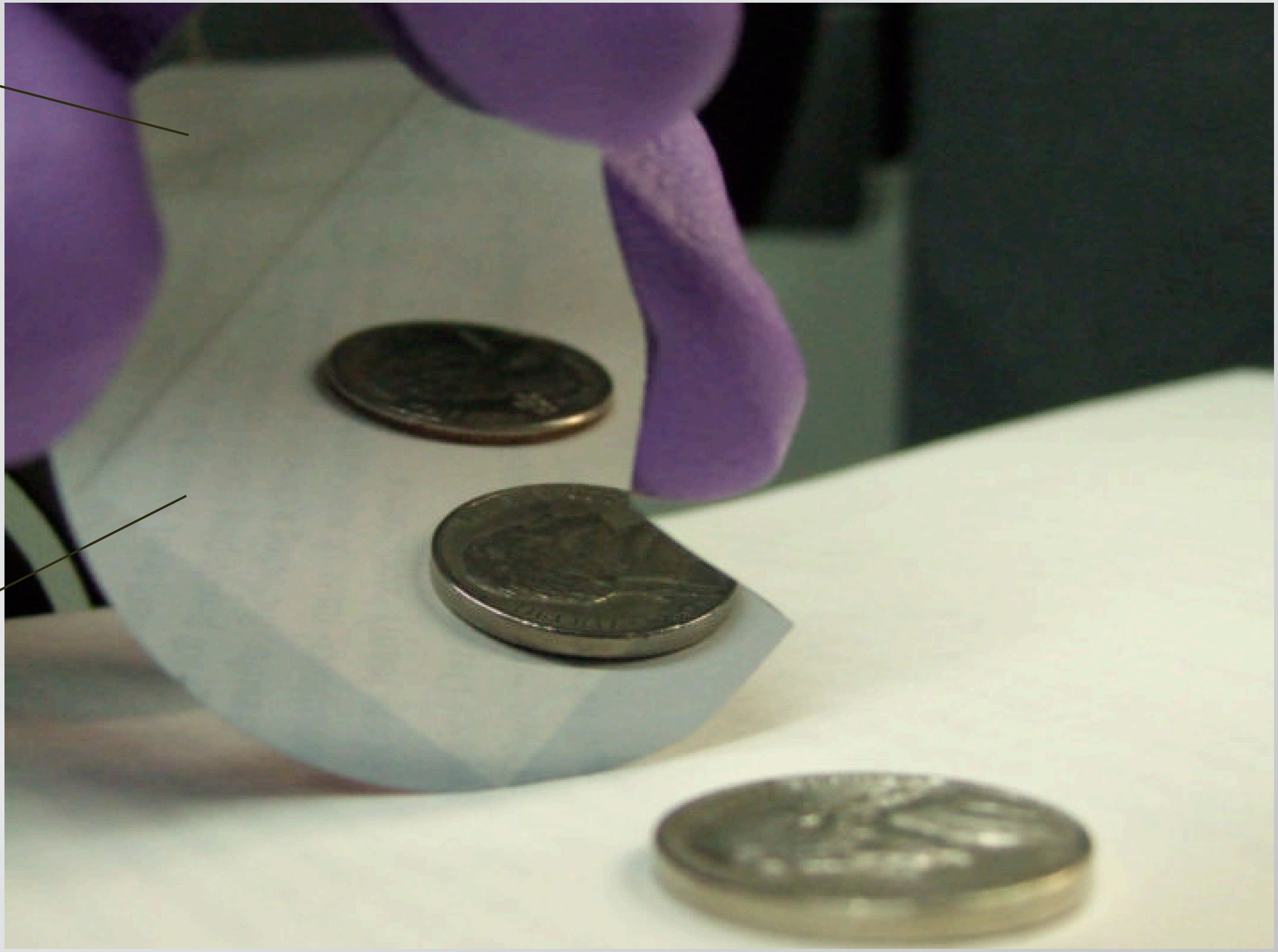


doped

Nontransparent materials

decouple ablation from melting

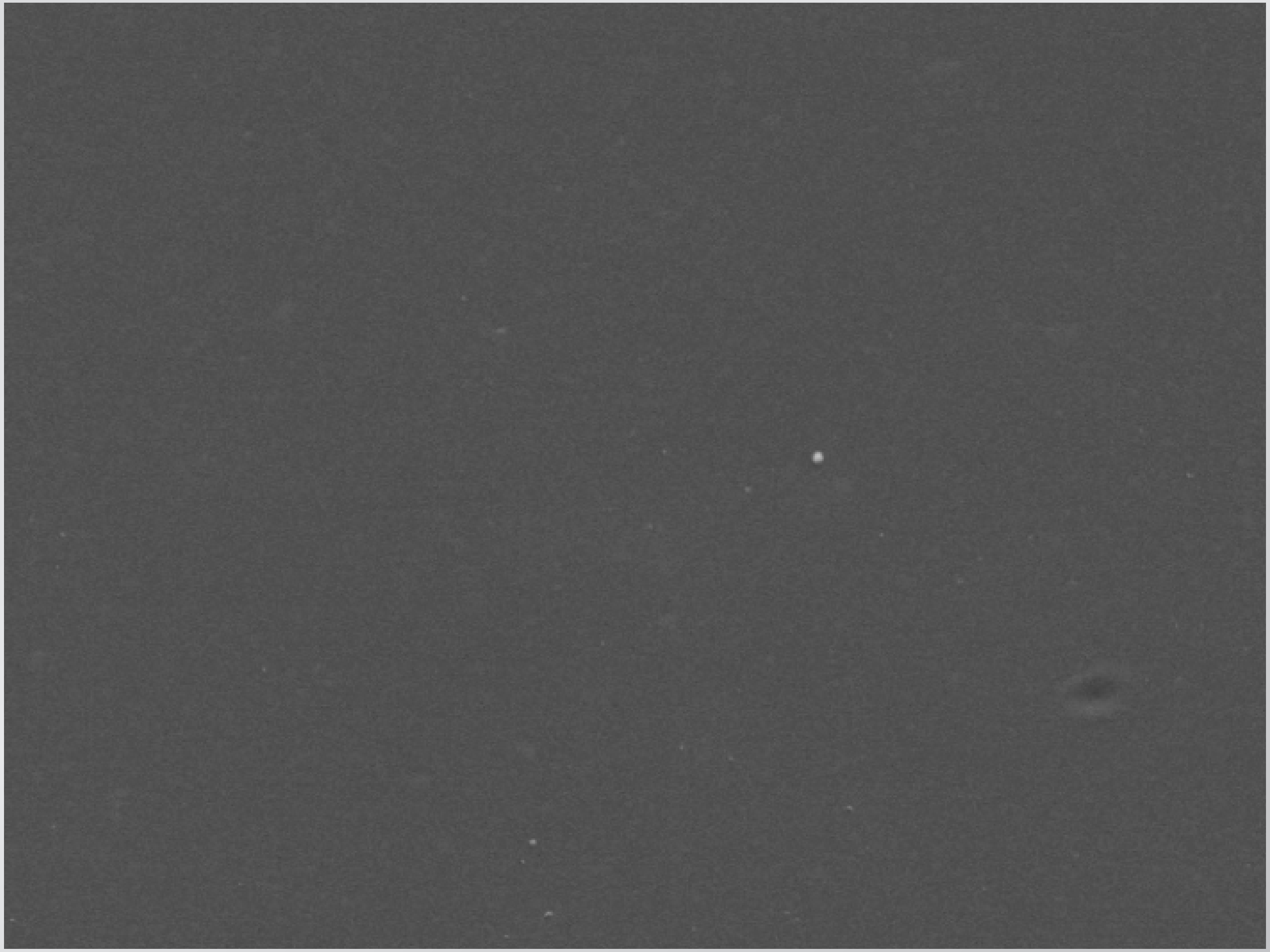
undoped



doped

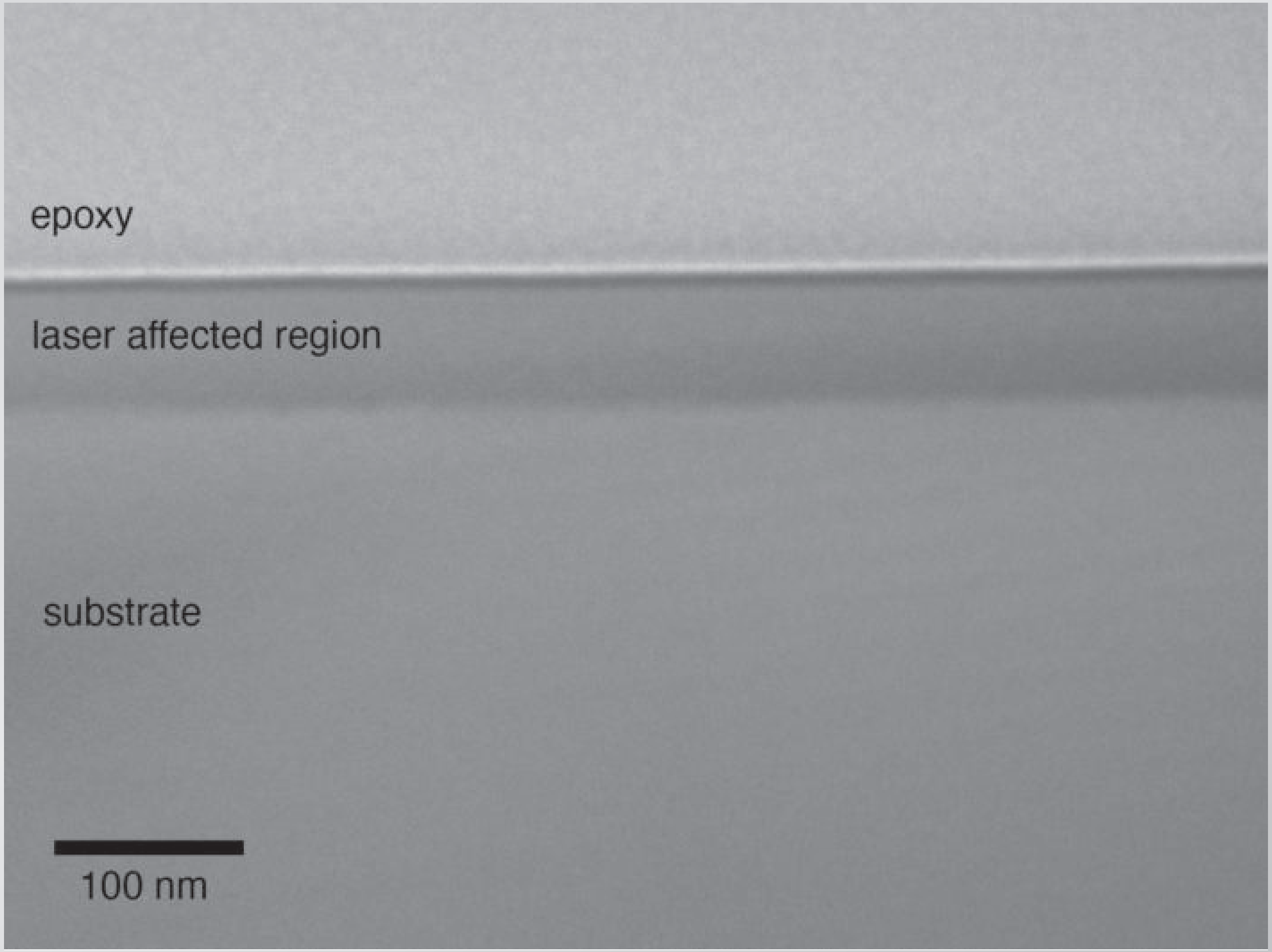
Nontransparent materials

decouple ablation from melting



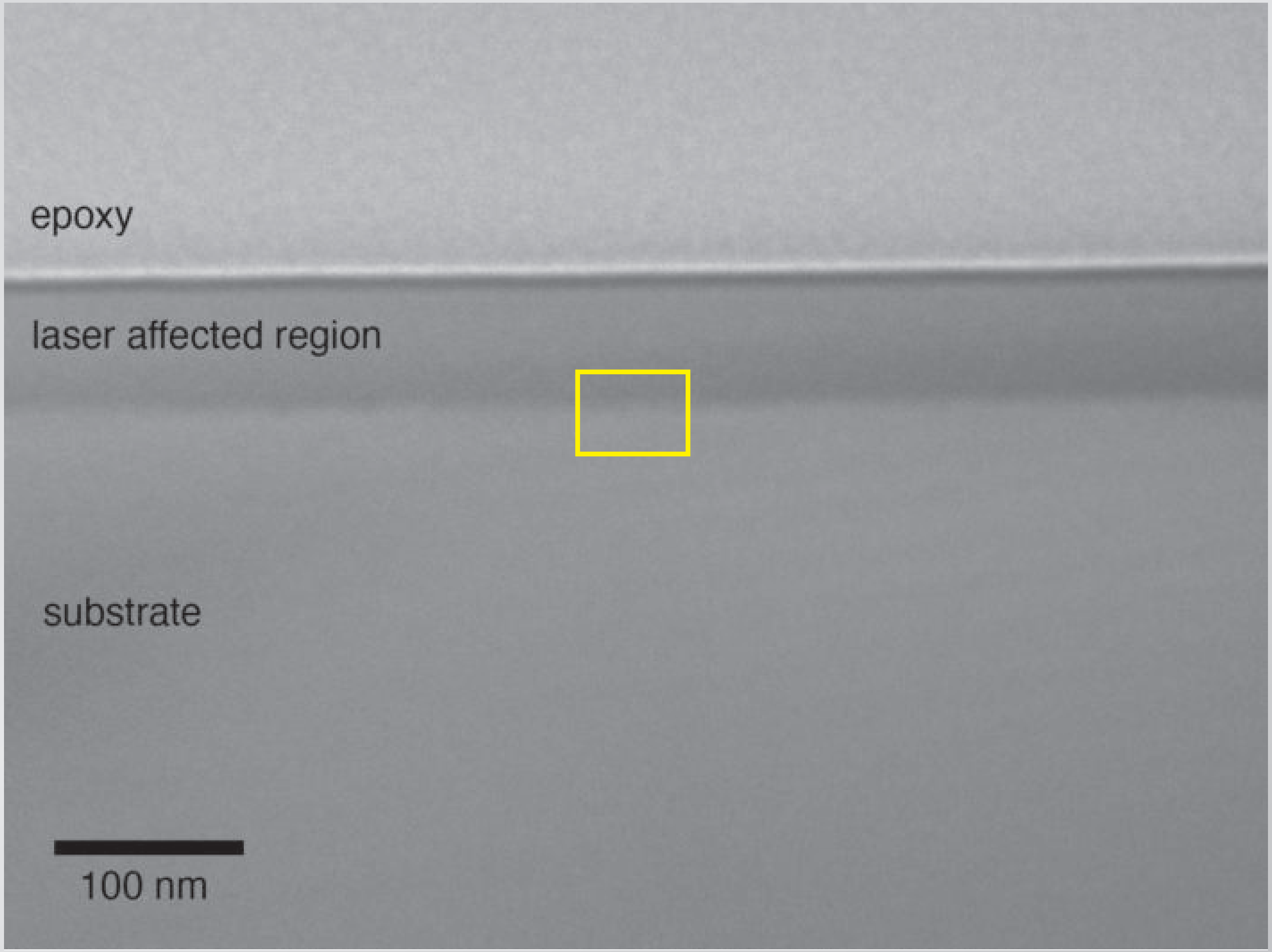
Nontransparent materials

decouple ablation from melting



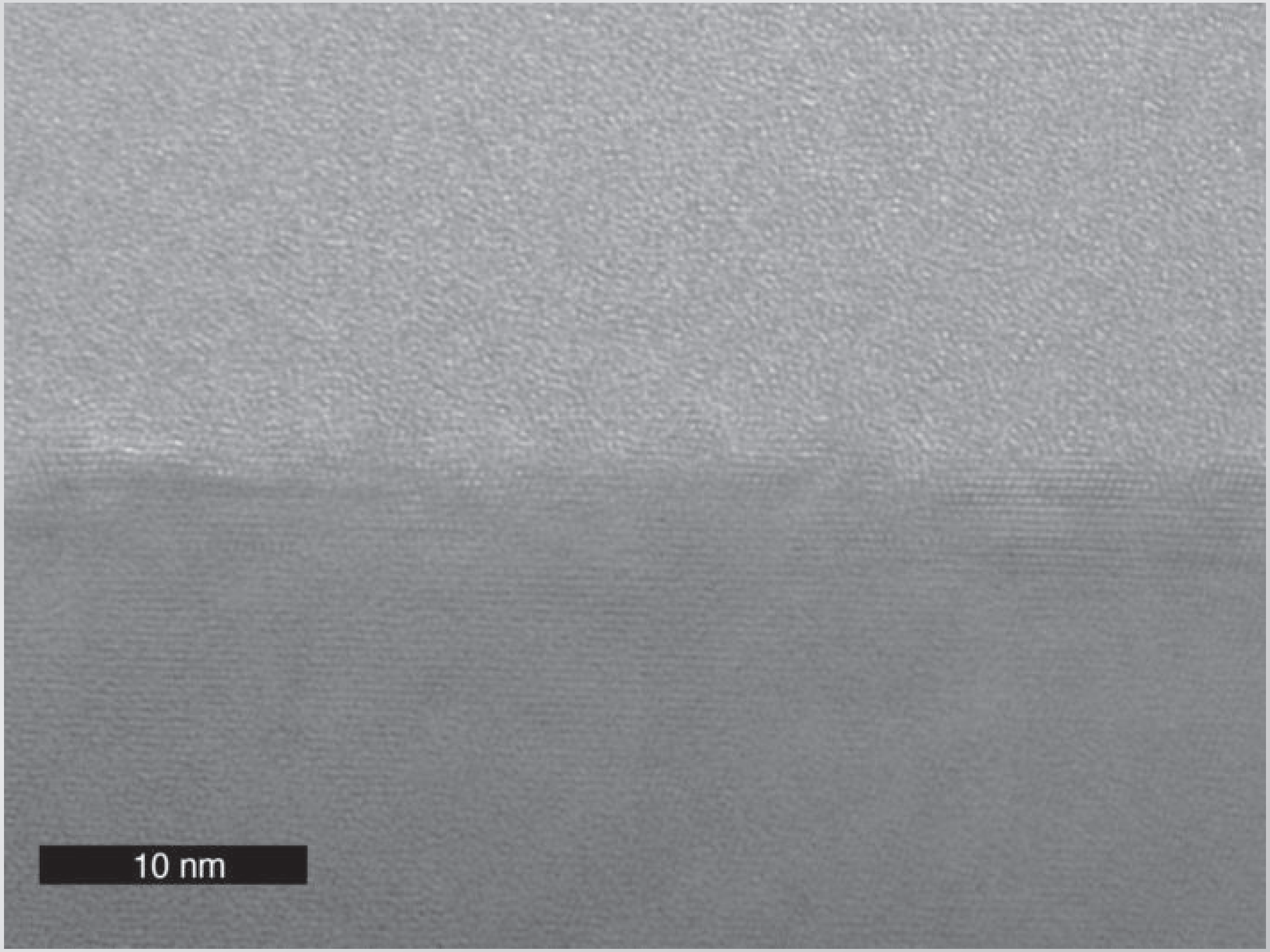
Nontransparent materials

decouple ablation from melting



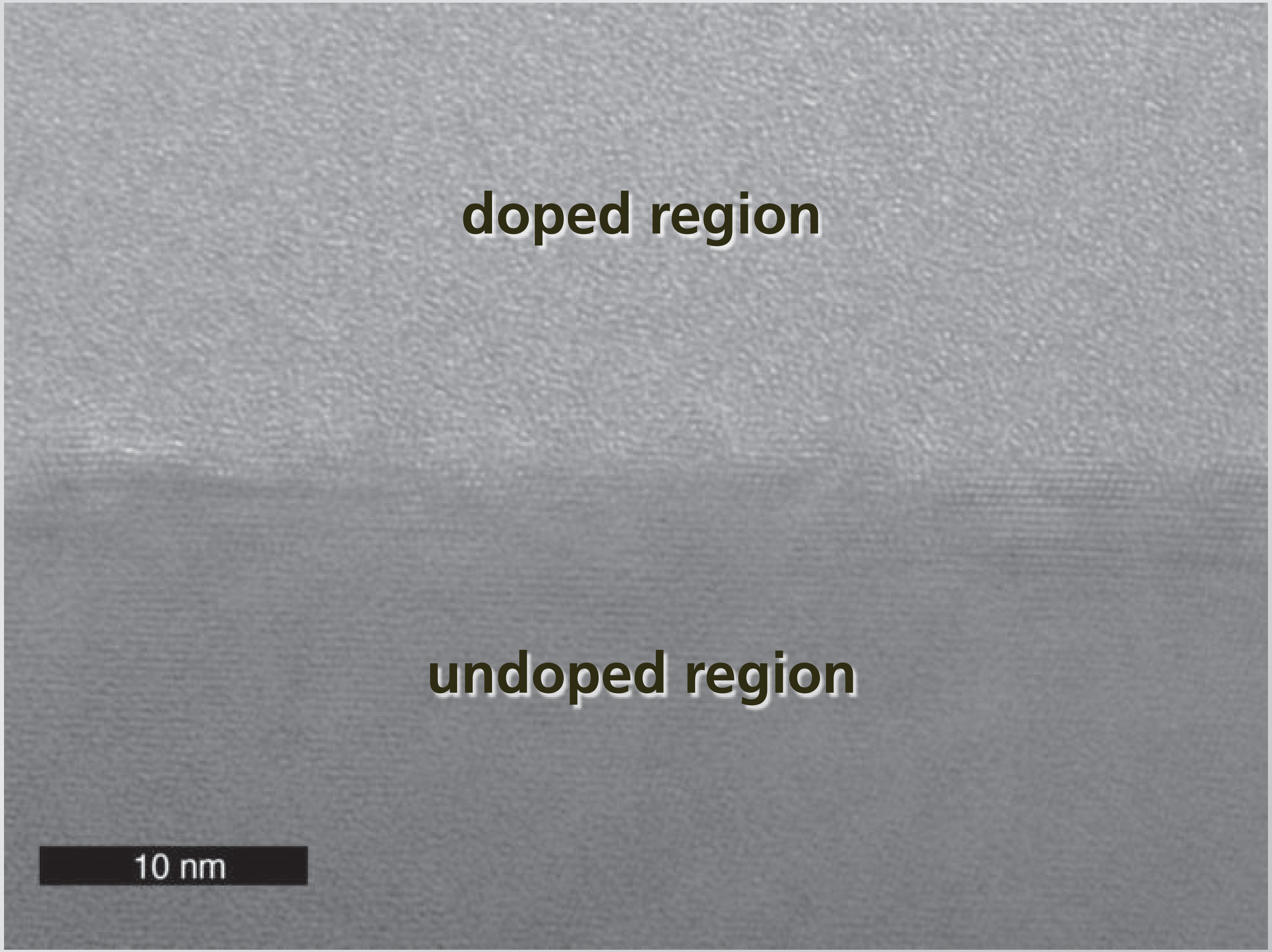
Nontransparent materials

decouple ablation from melting



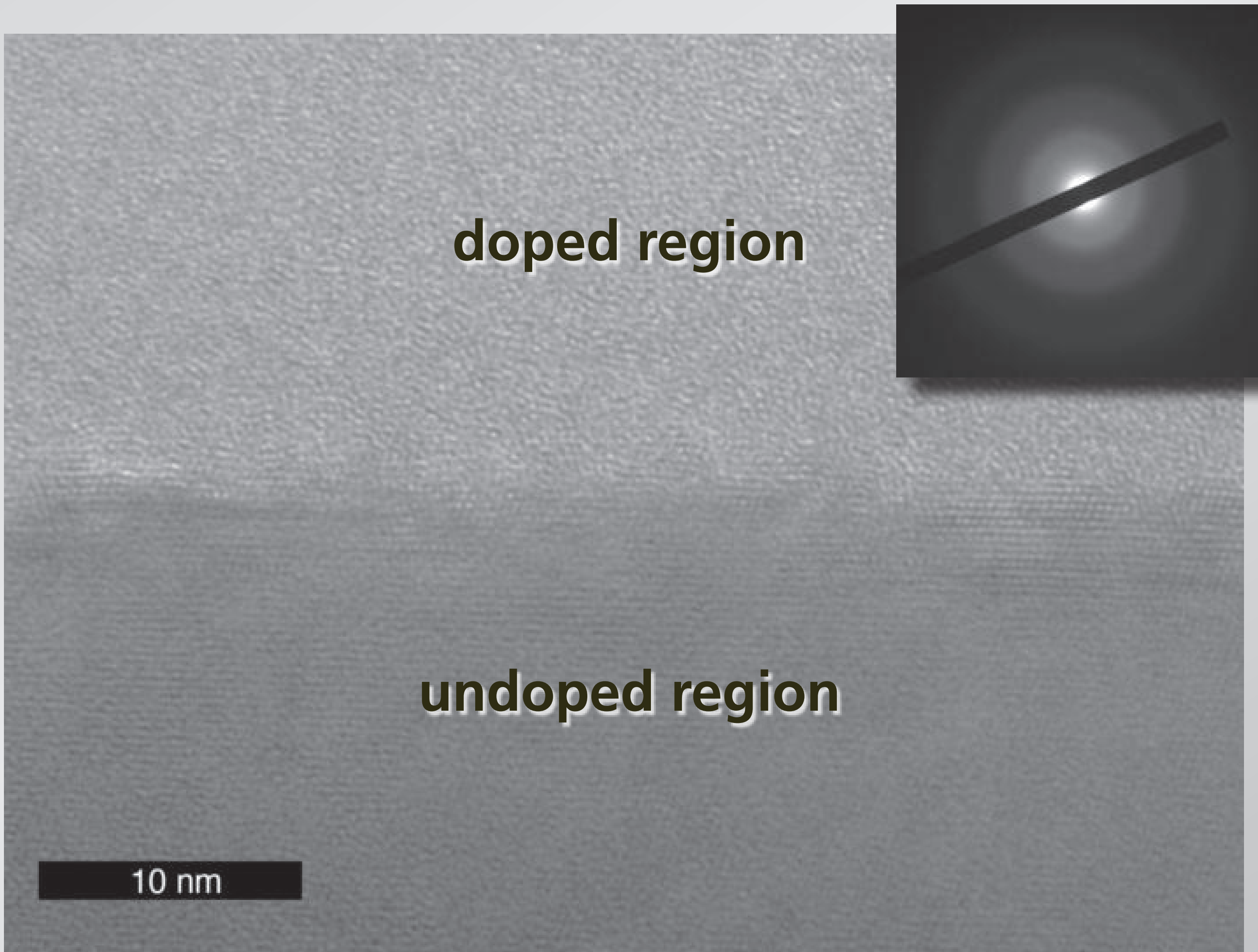
Nontransparent materials

decouple ablation from melting



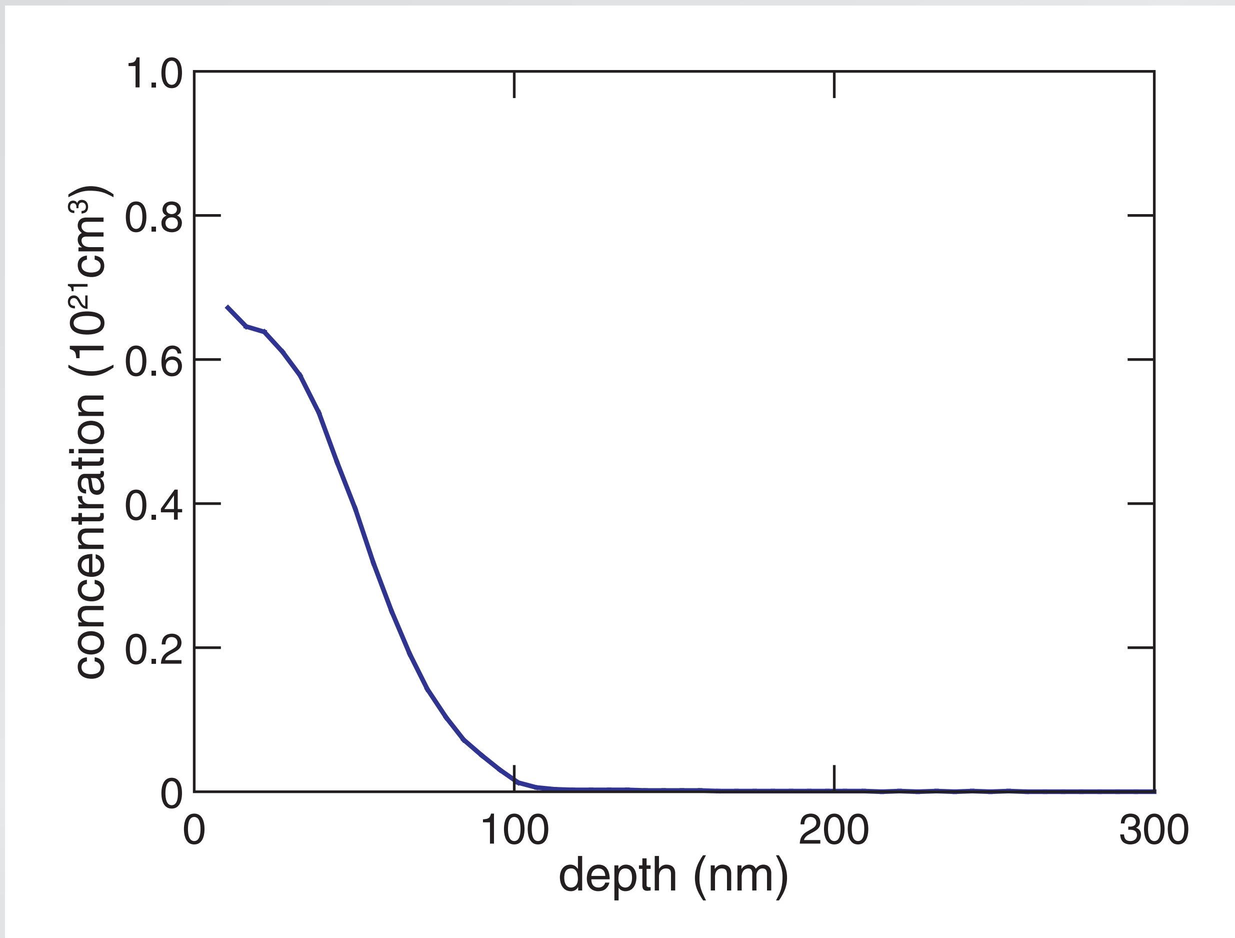
Nontransparent materials

decouple ablation from melting

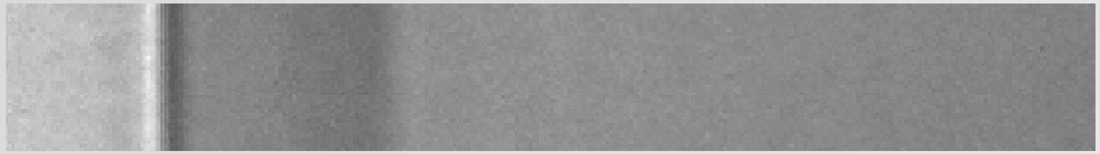


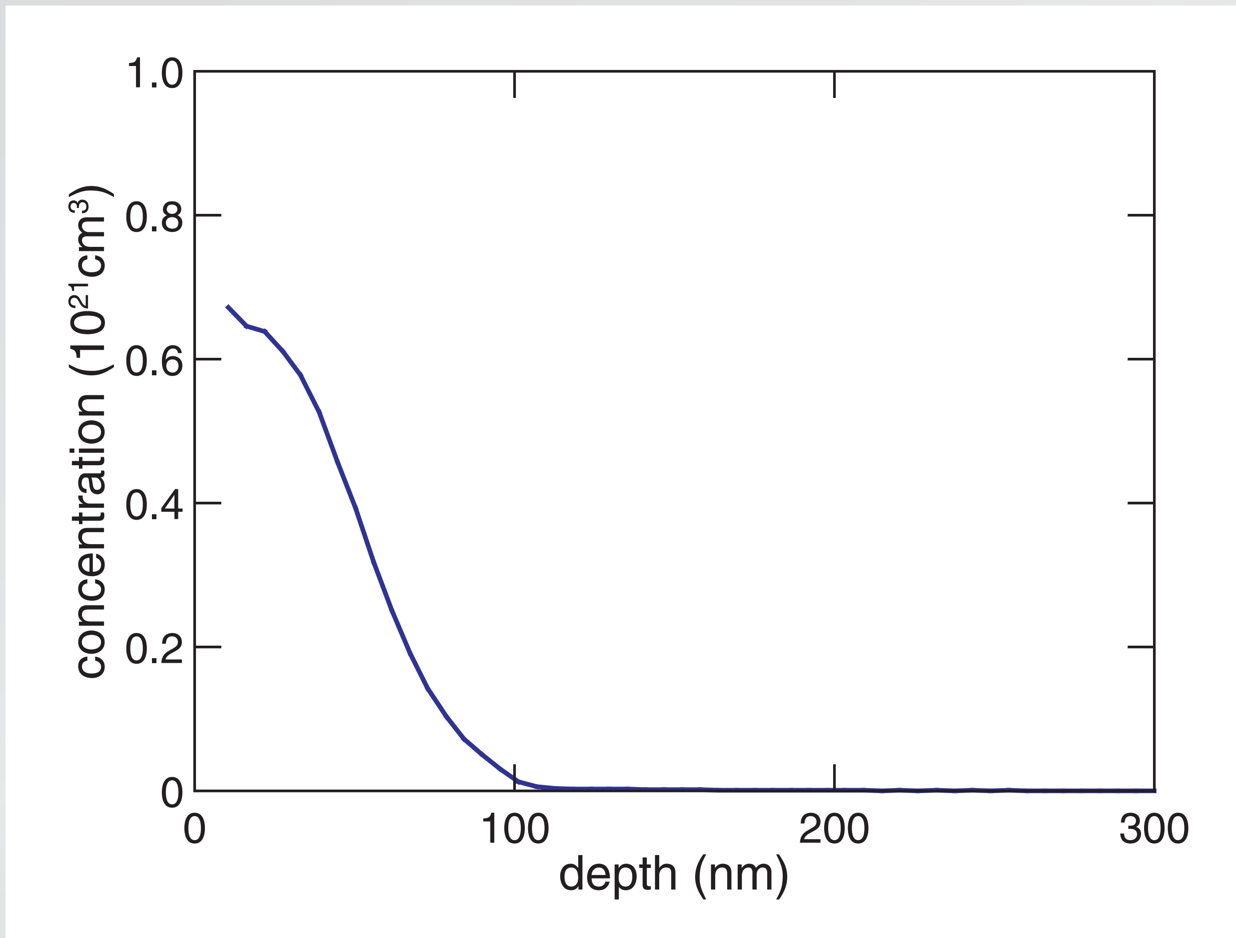
Nontransparent materials

secondary ion mass spectrometry



Nontransparent materials





Nontransparent materials

Things to keep in mind

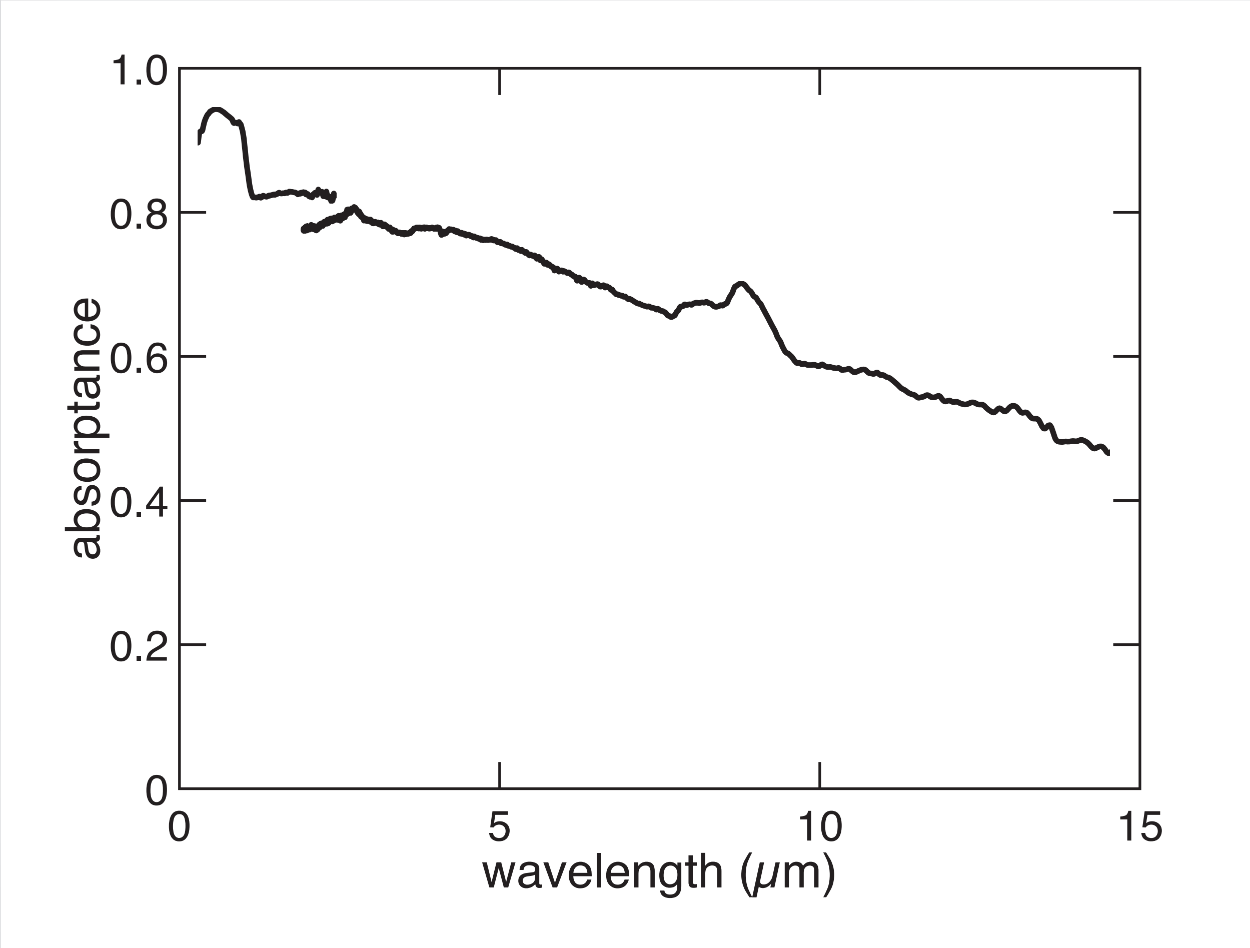
- rapid melting and resolidification causes doping
- ablation causes morphology changes
- about 1% impurity in 100-nm thick surface layer

Outline

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

Optical hyperdoping

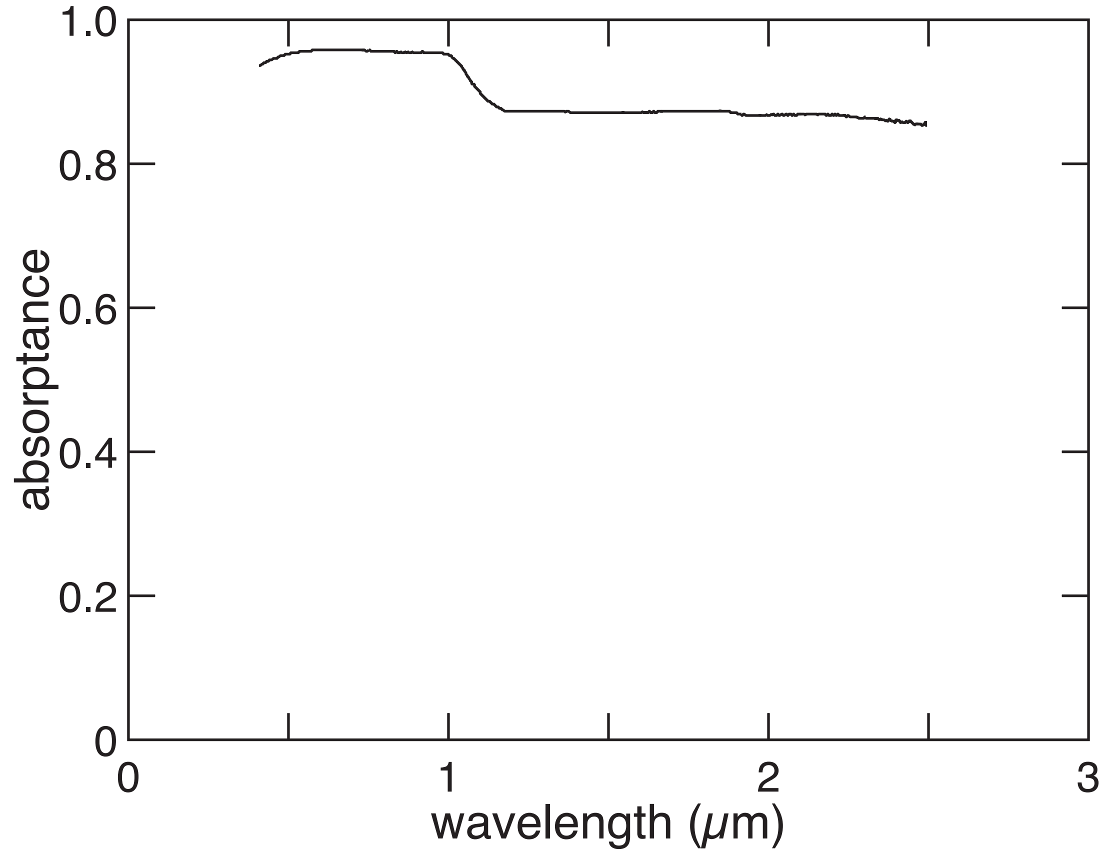
absorptance (1 – R_{int} – T_{int})



Asenbaum, Vienna

Optical hyperdoping

effect of annealing on IR absorptance

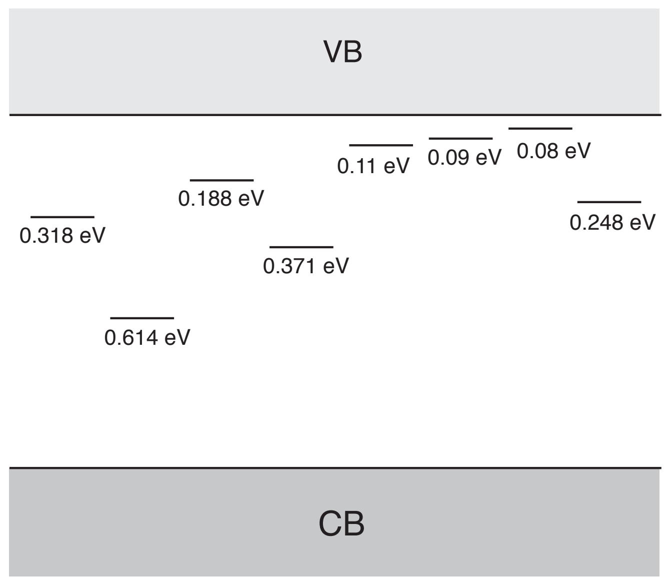


Optical hyperdoping

what dopant states/bands cause IR absorption?

Optical hyperdoping

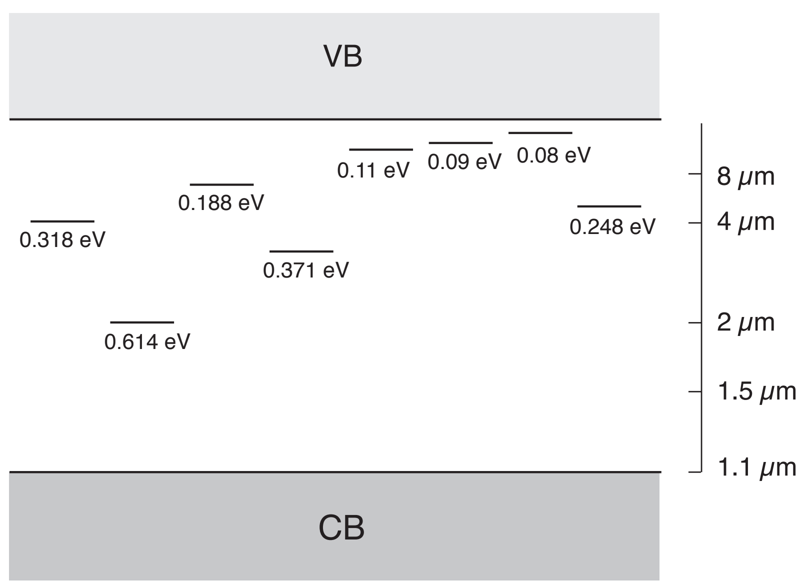
1 part in 10^6 sulfur introduces donor states in gap



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

Optical hyperdoping

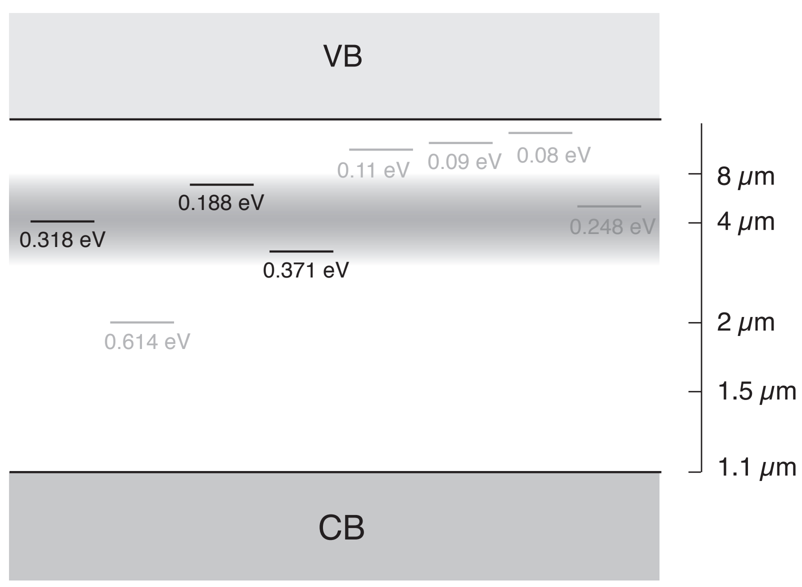
1 part in 10^6 sulfur introduces donor states in gap



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

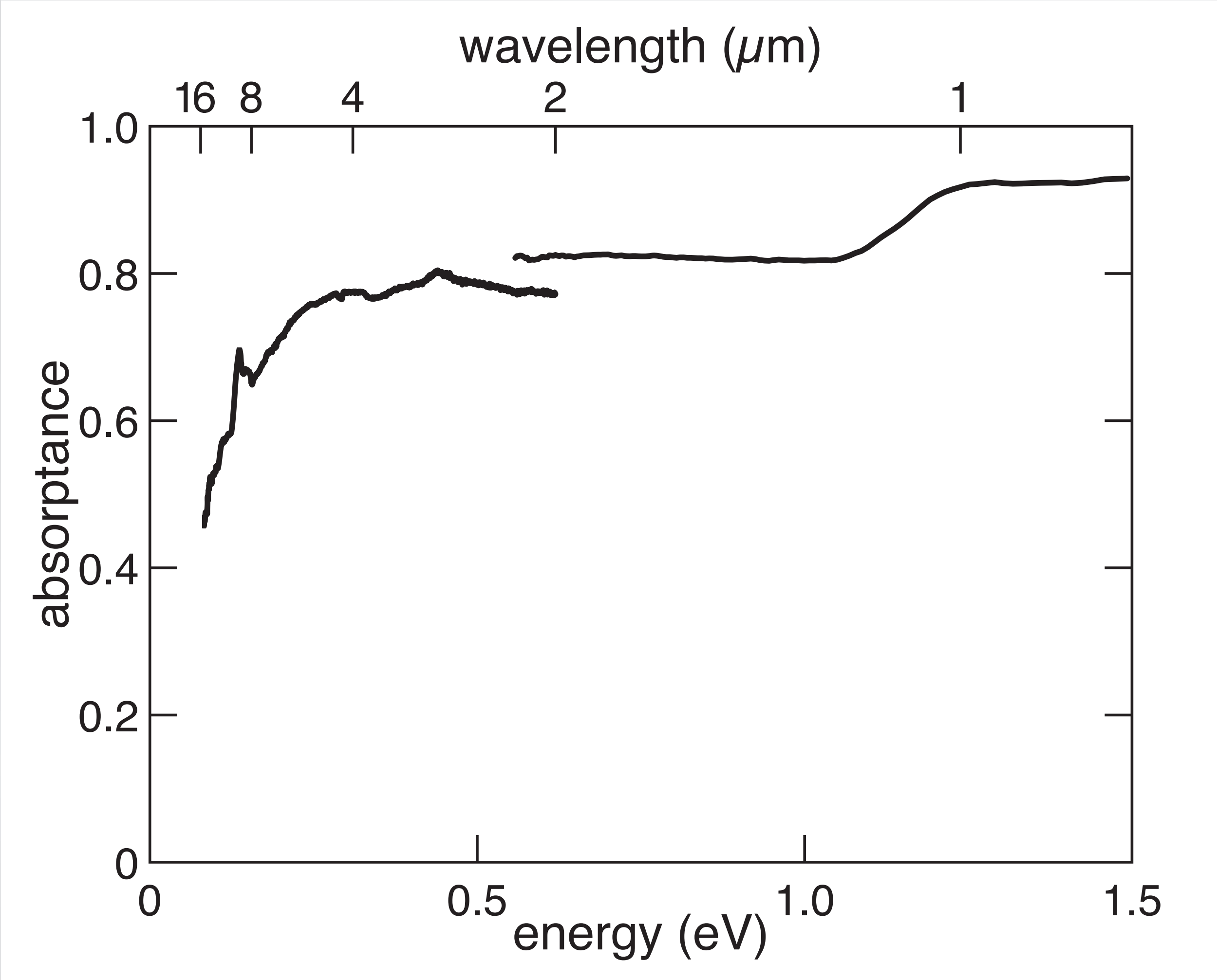
Optical hyperdoping

at high concentration states broaden into band



Optical hyperdoping

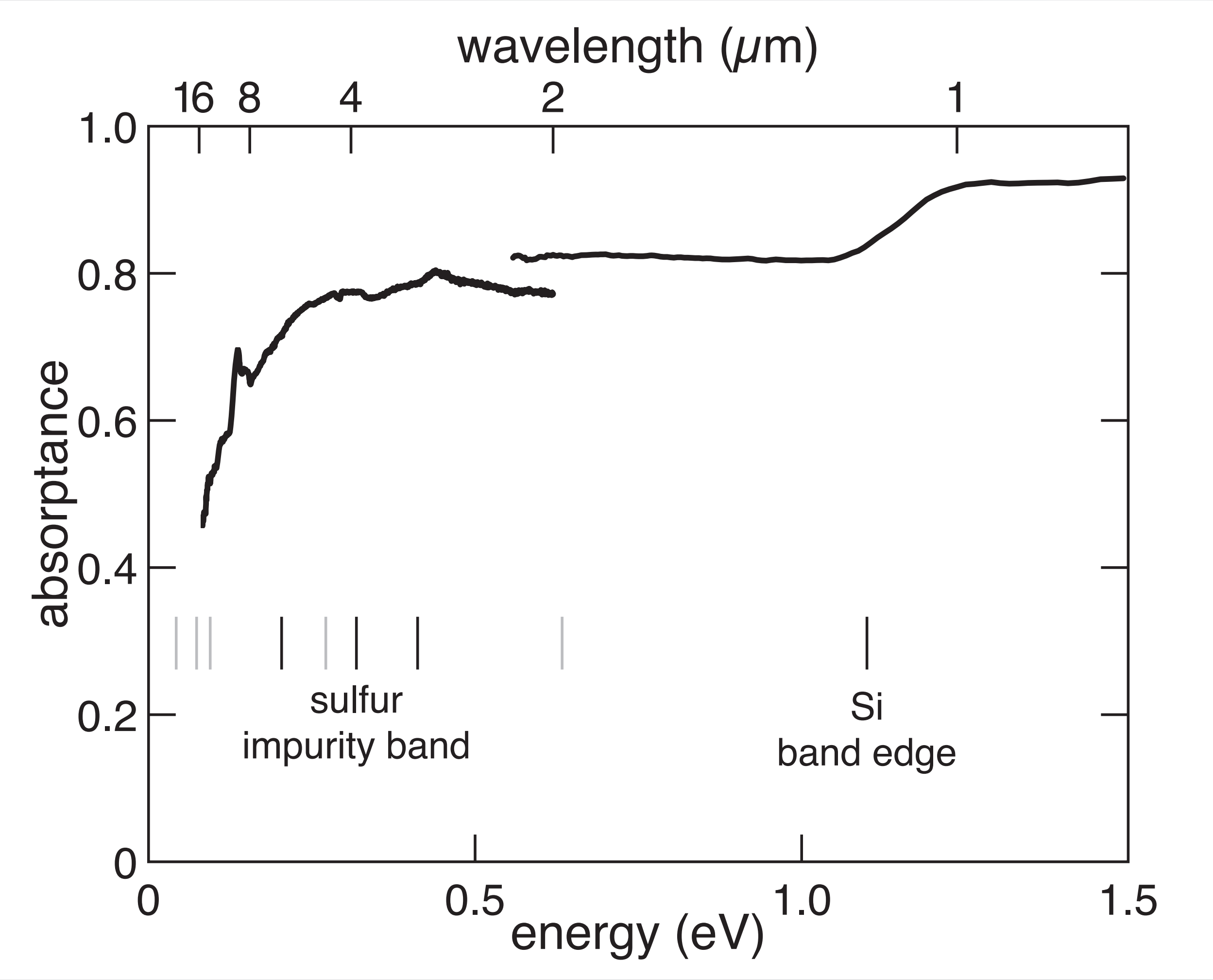
absorptance ($1 - R_{int} - T_{int}$)



Asenbaum, Vienna

Optical hyperdoping

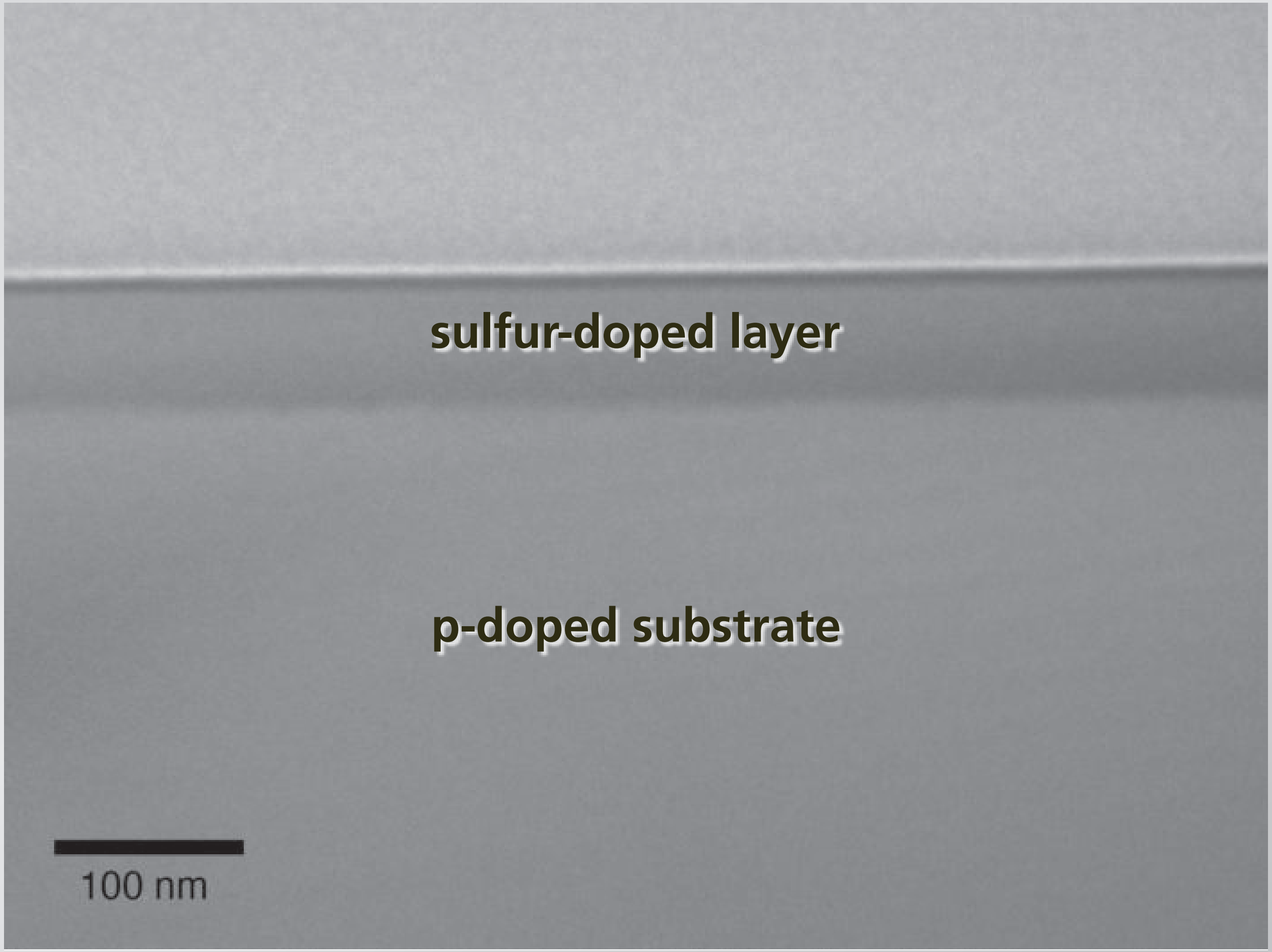
absorptance ($1 - R_{int} - T_{int}$)



Asenbaum, Vienna

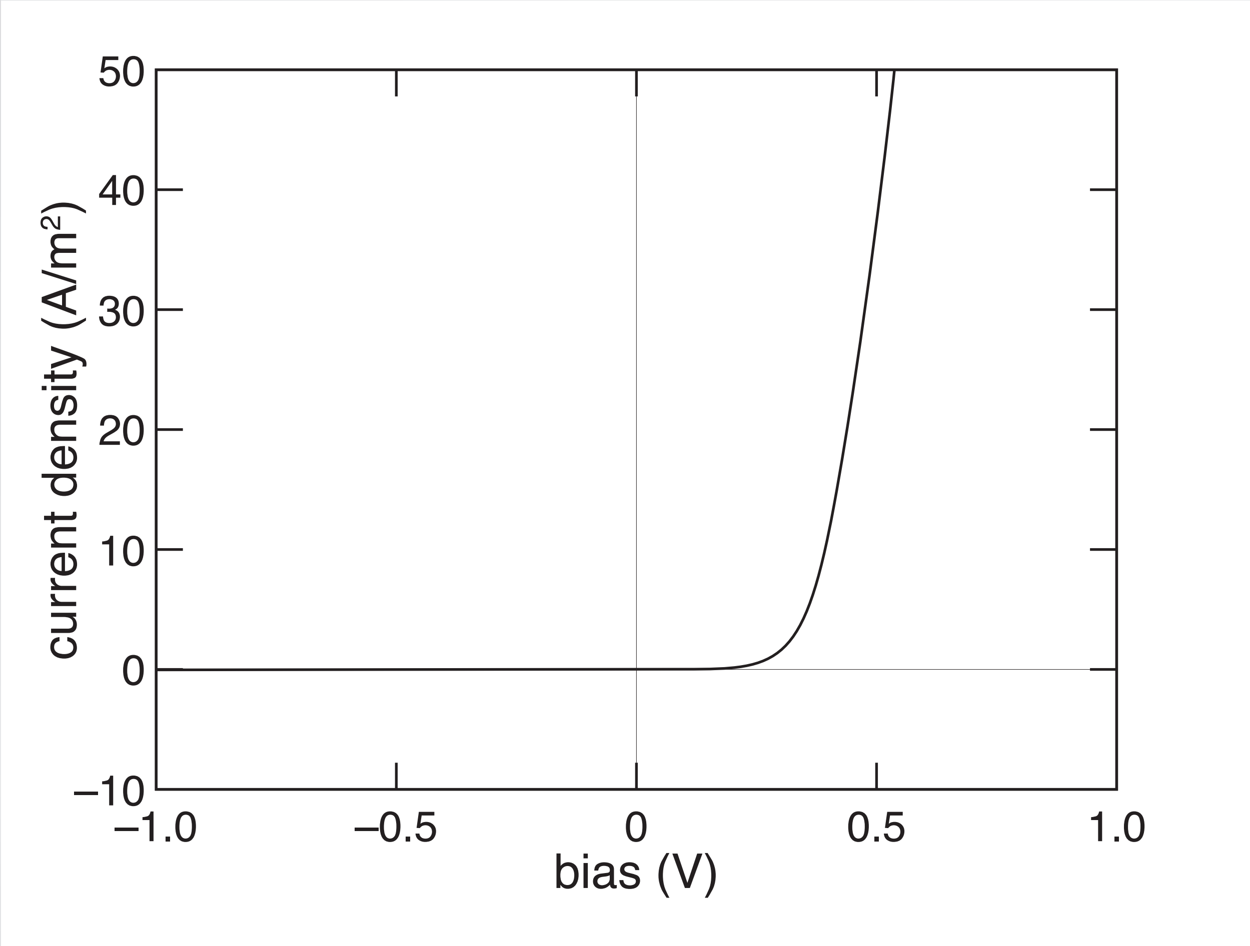
Optical hyperdoping

should have shallow junction below surface



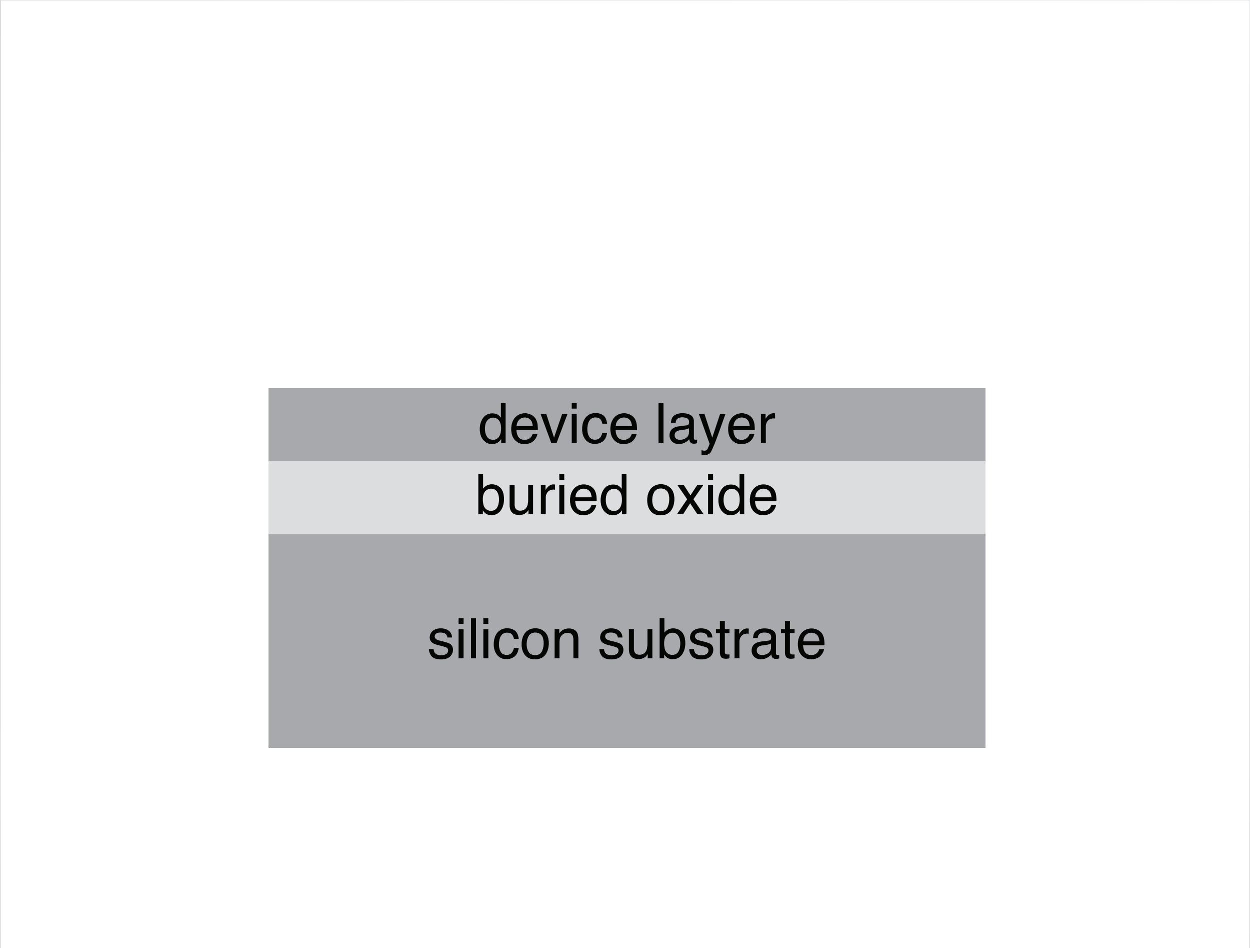
Optical hyperdoping

excellent rectification (after annealing)



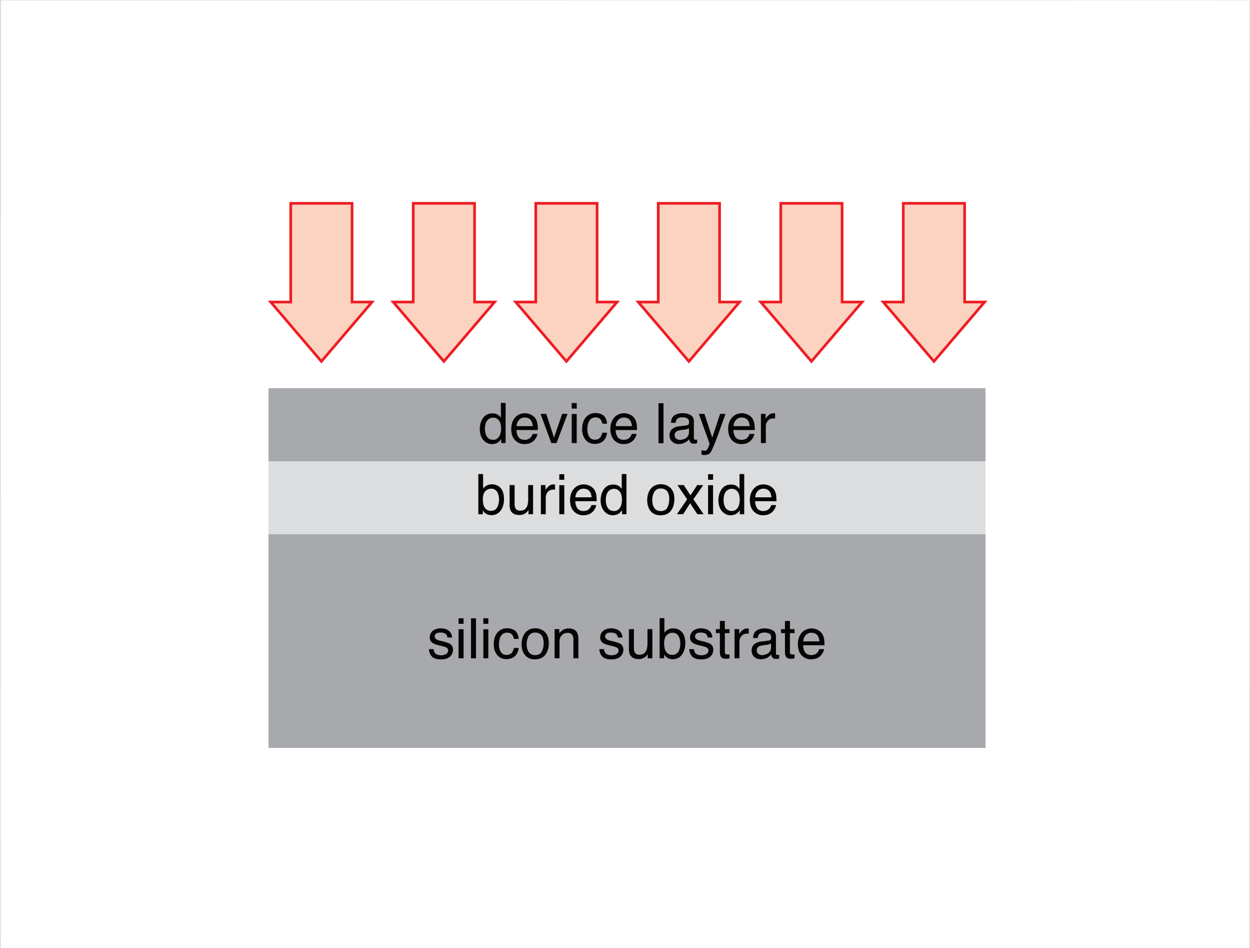
Optical hyperdoping

isolate surface layer for Hall measurements



Optical hyperdoping

isolate surface layer for Hall measurements



Optical hyperdoping

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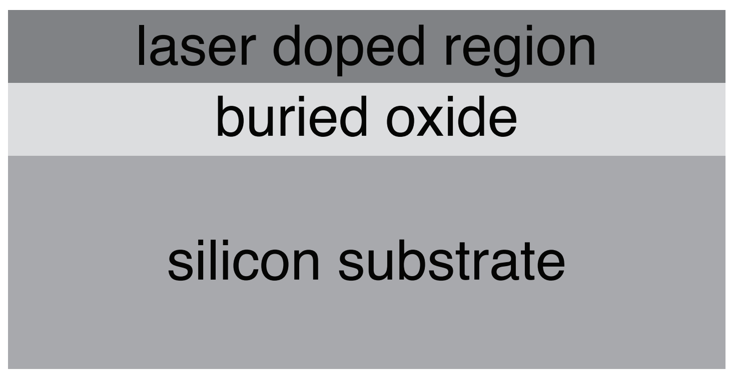

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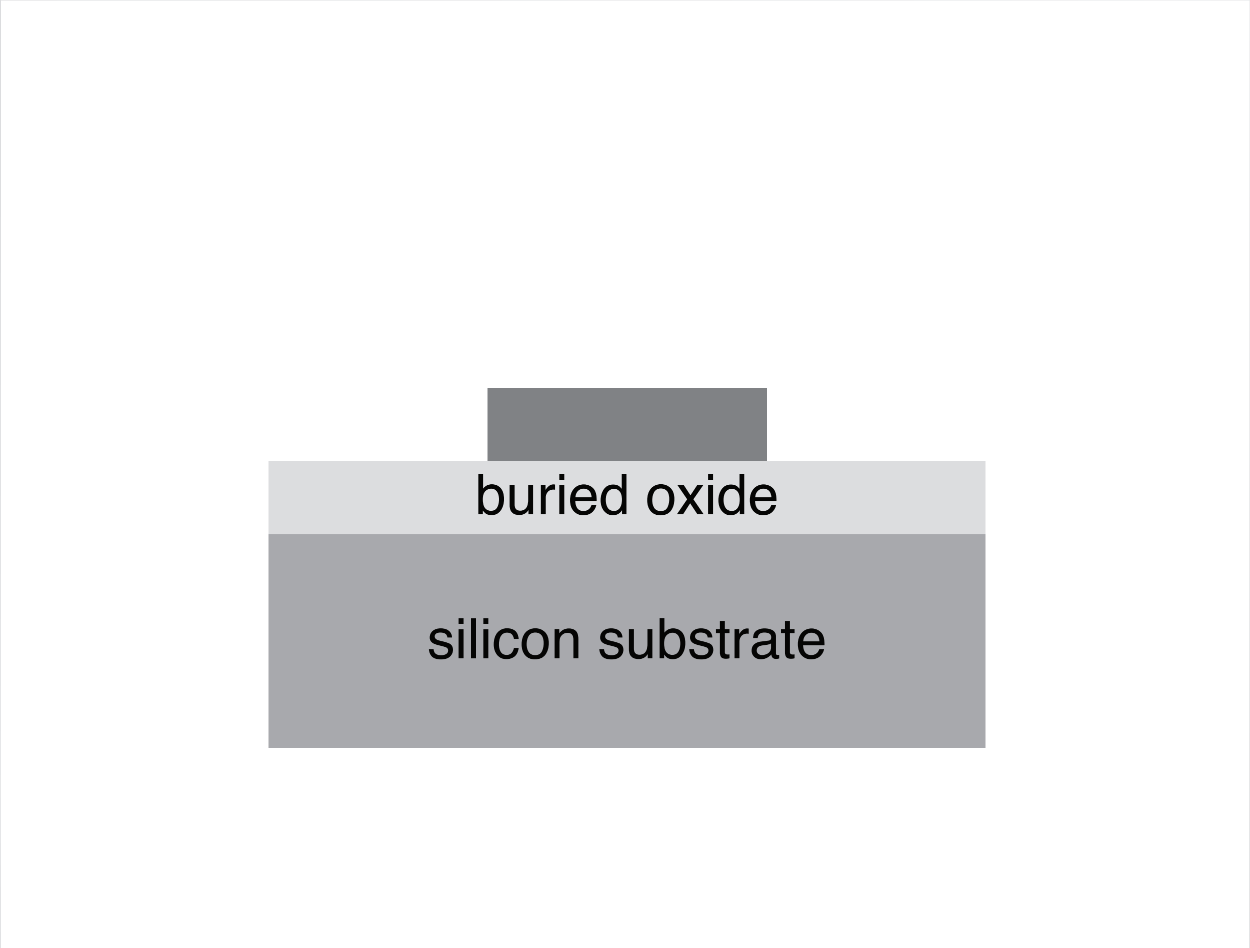

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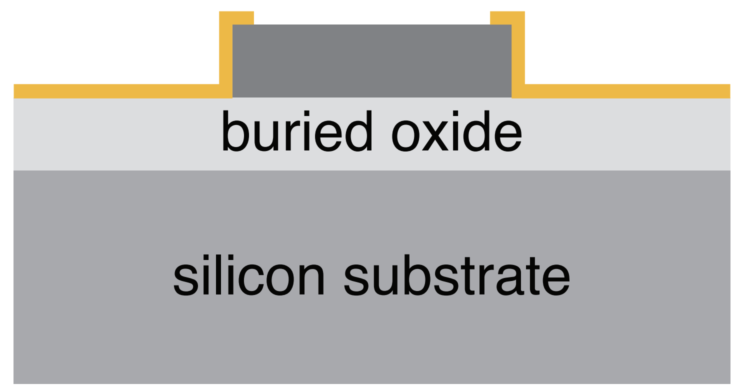

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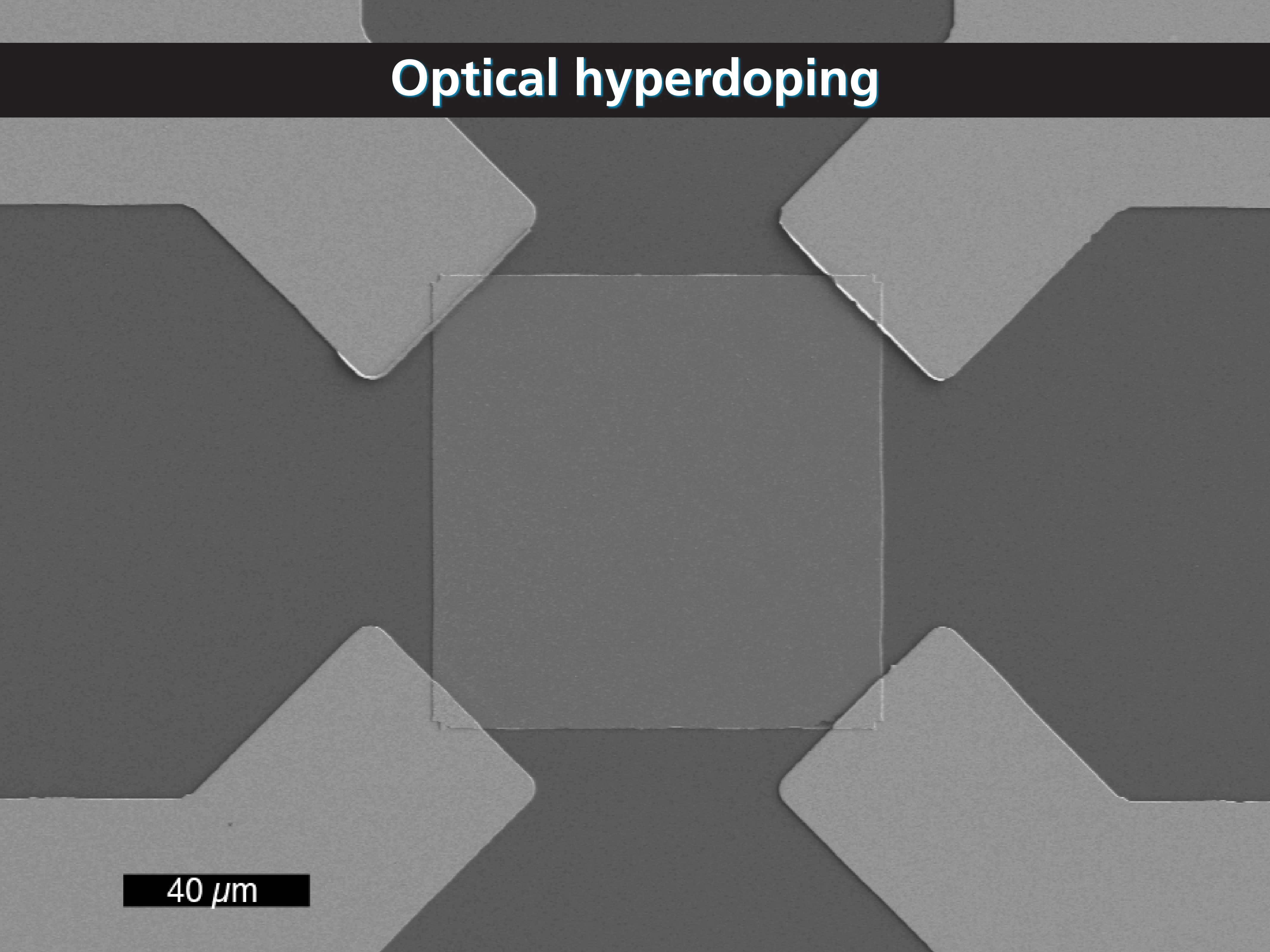
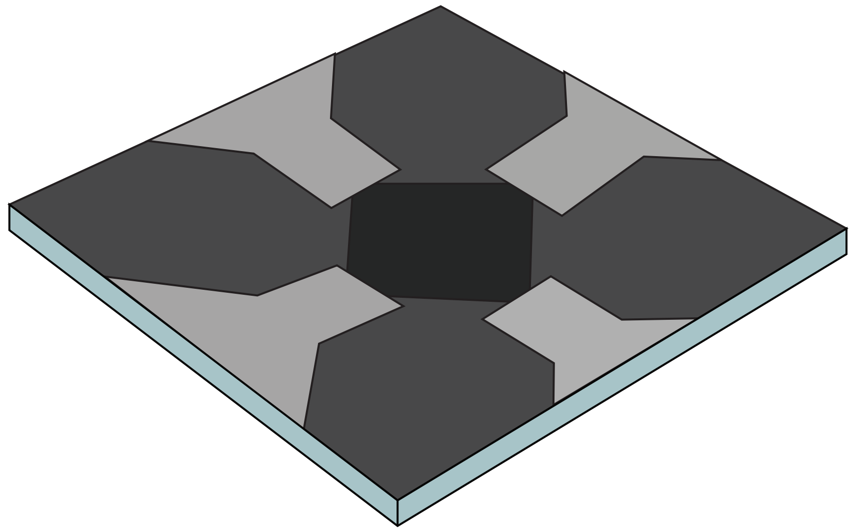


Optical hyperdoping

Hall measurements



Optical hyperdoping

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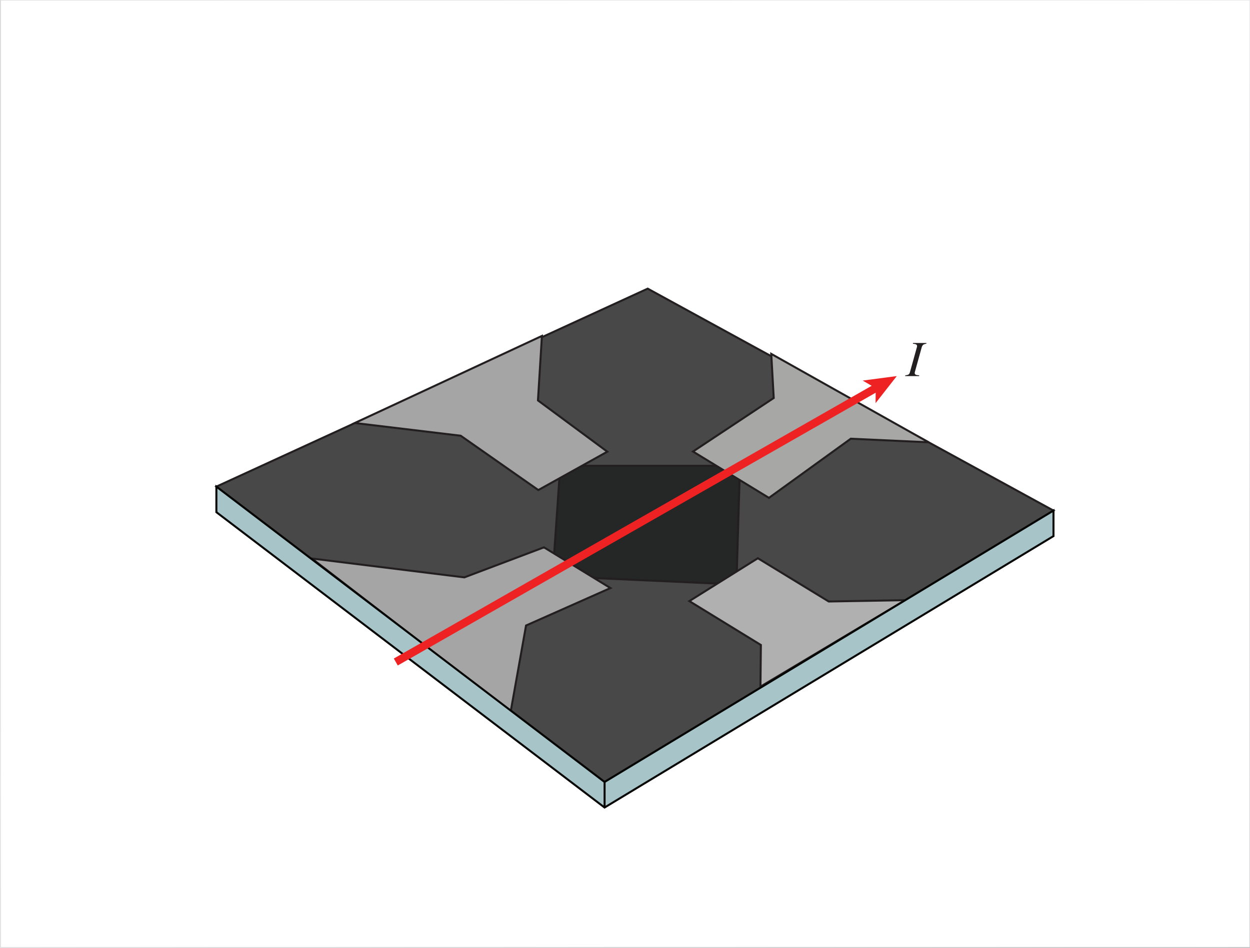

Optical hyperdoping

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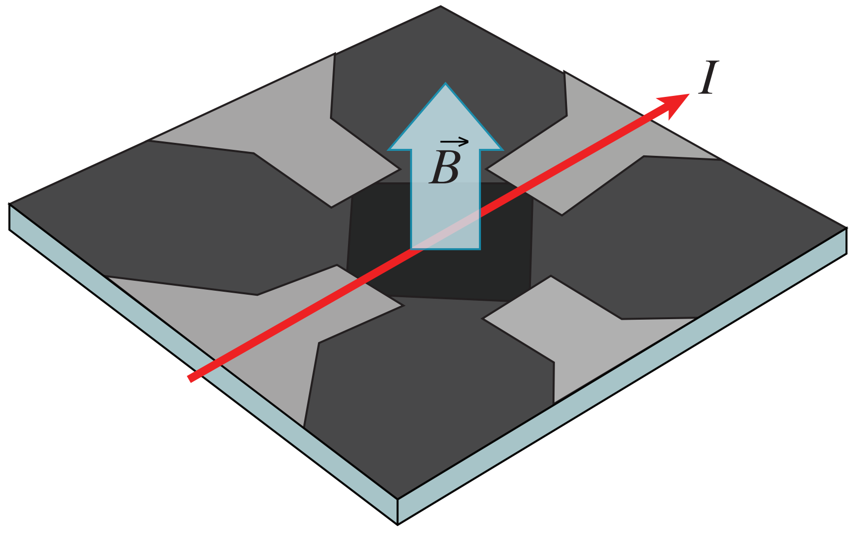

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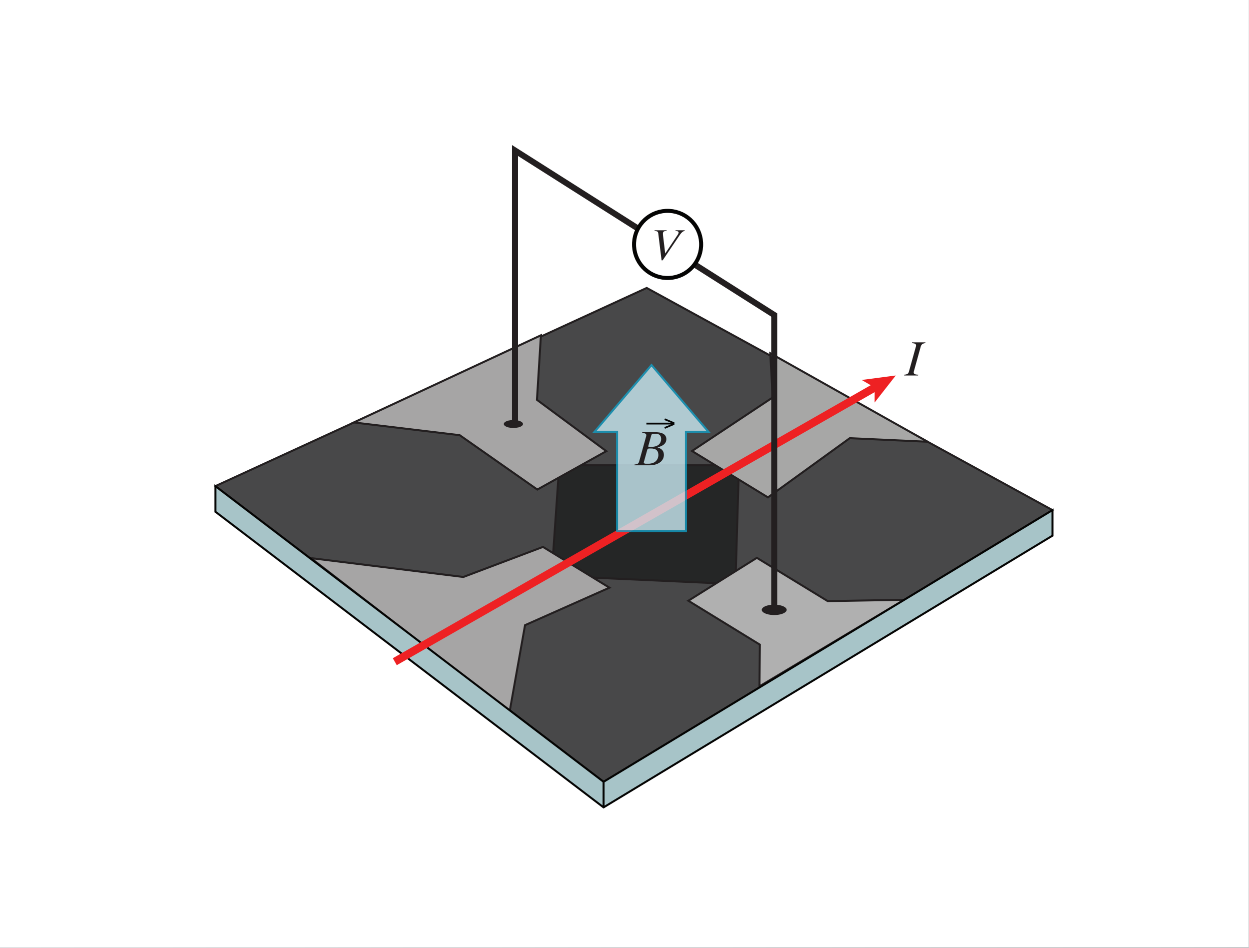
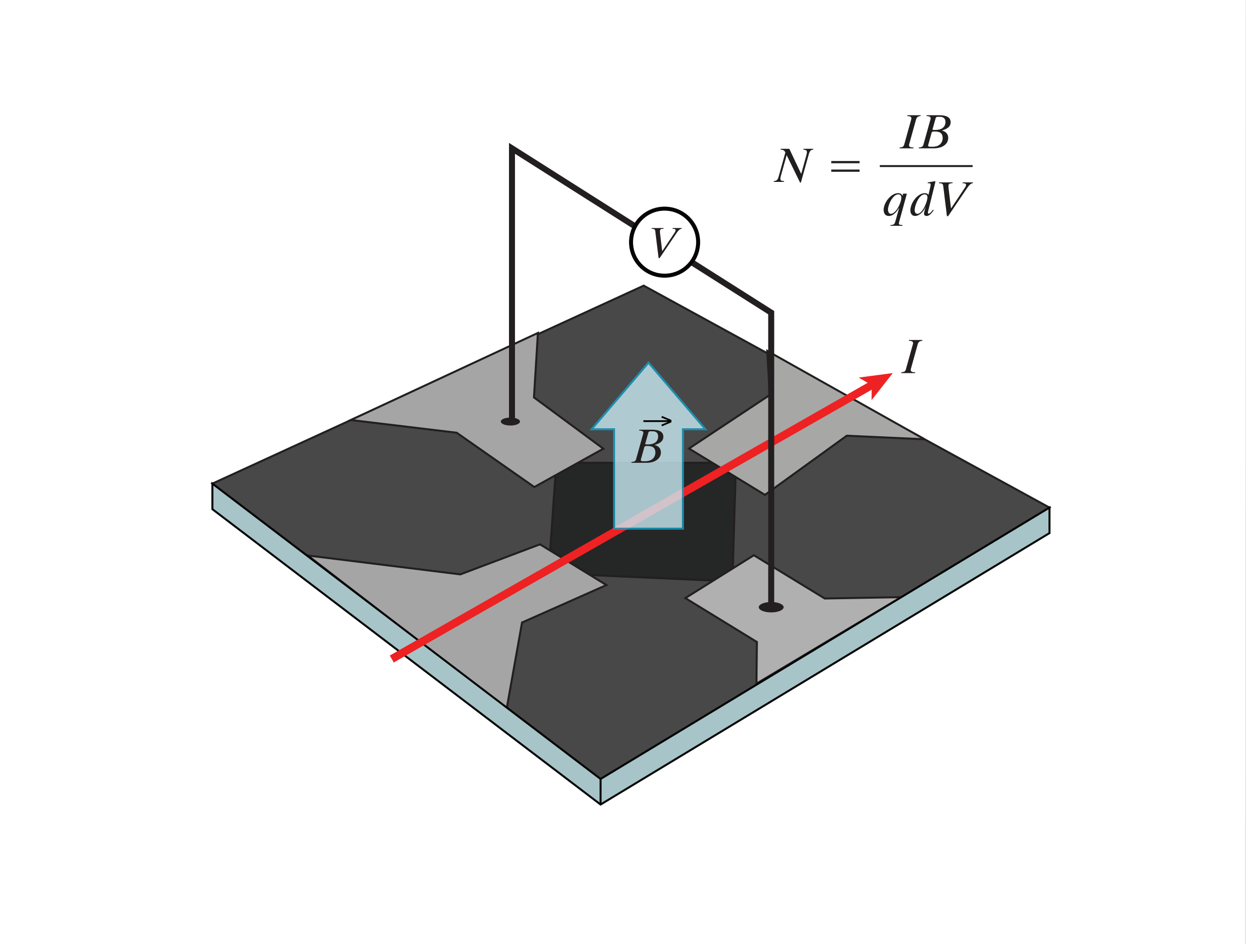


Optical hyperdoping

Hall measurements



Optical hyperdoping

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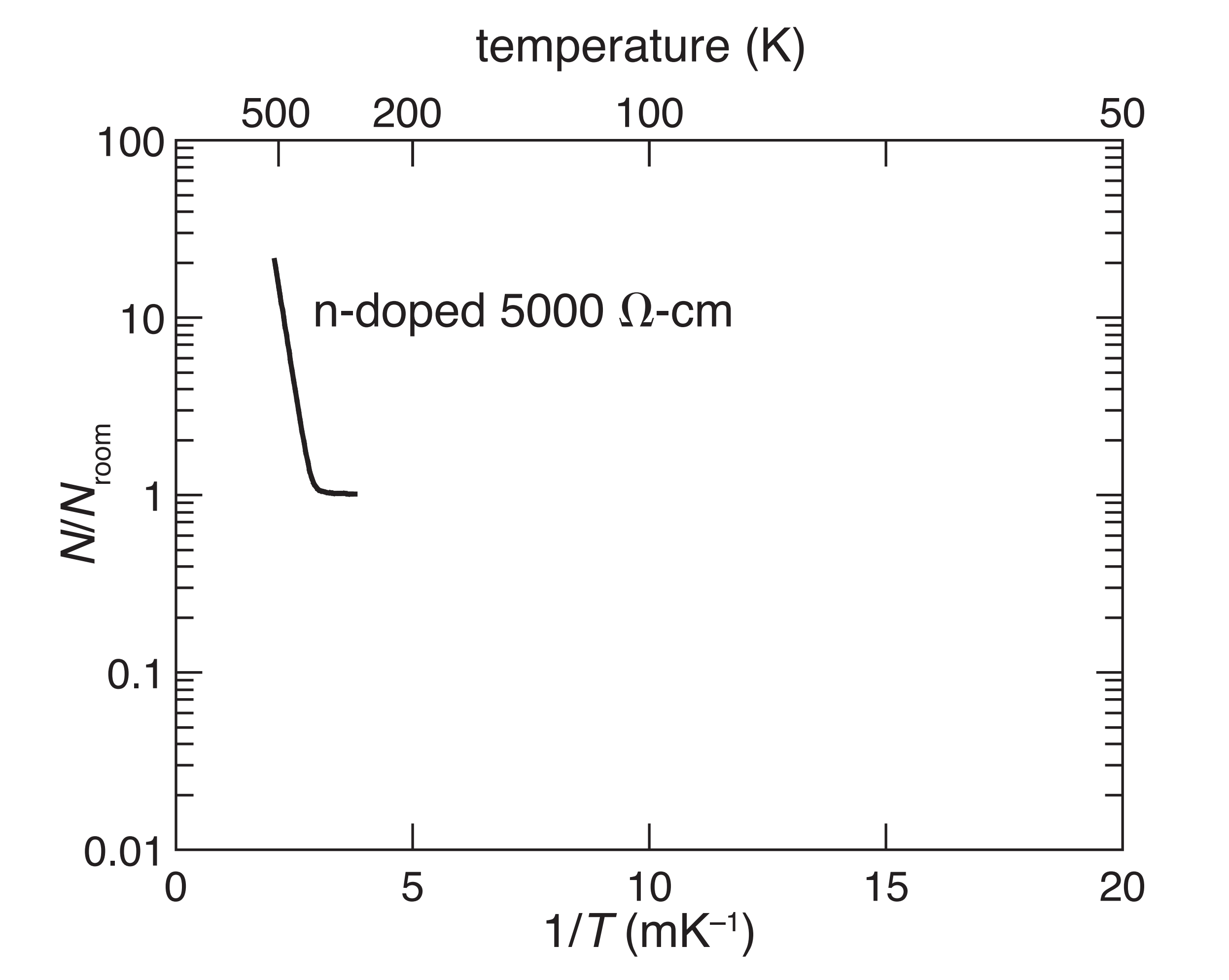

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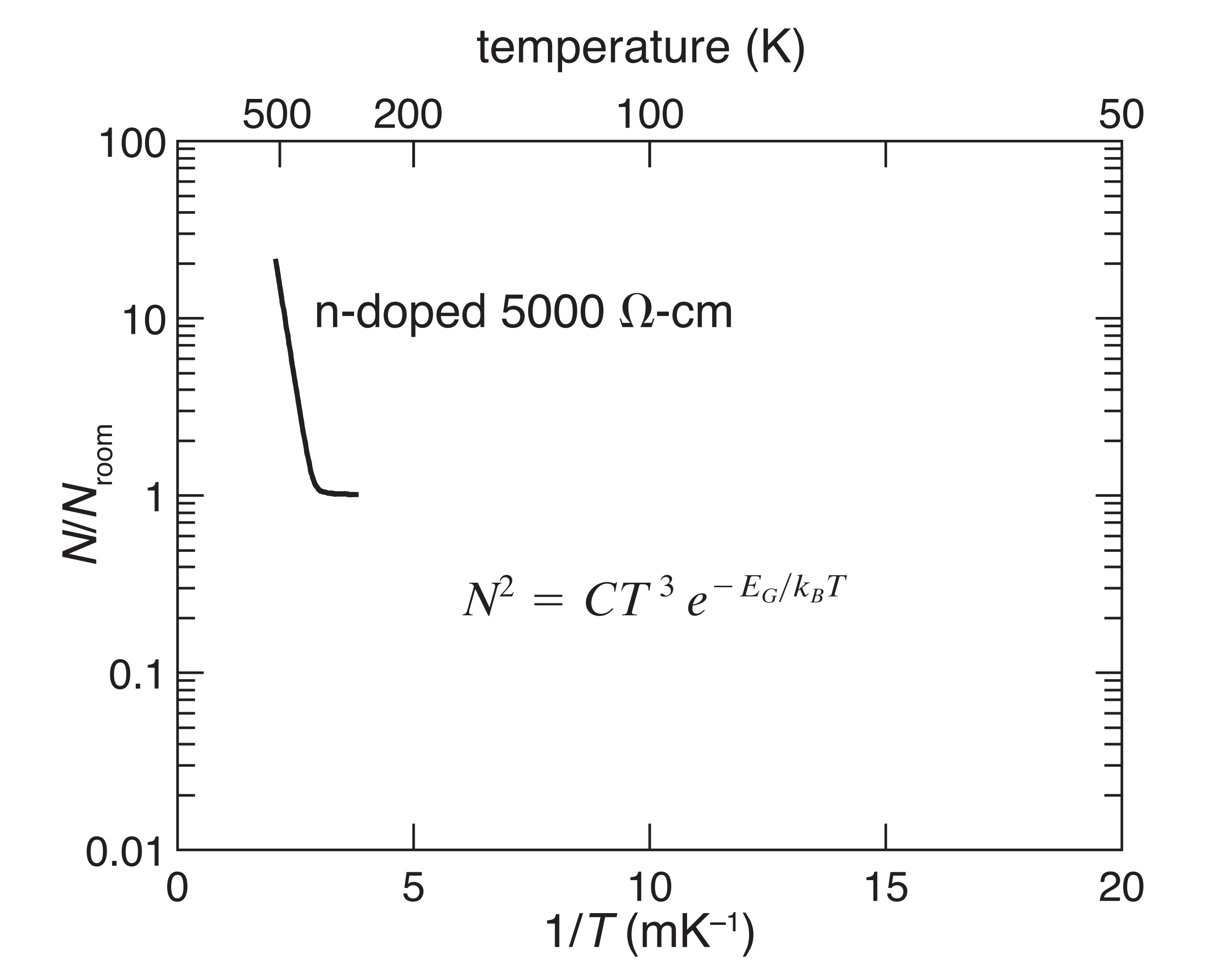

Optical hyperdoping

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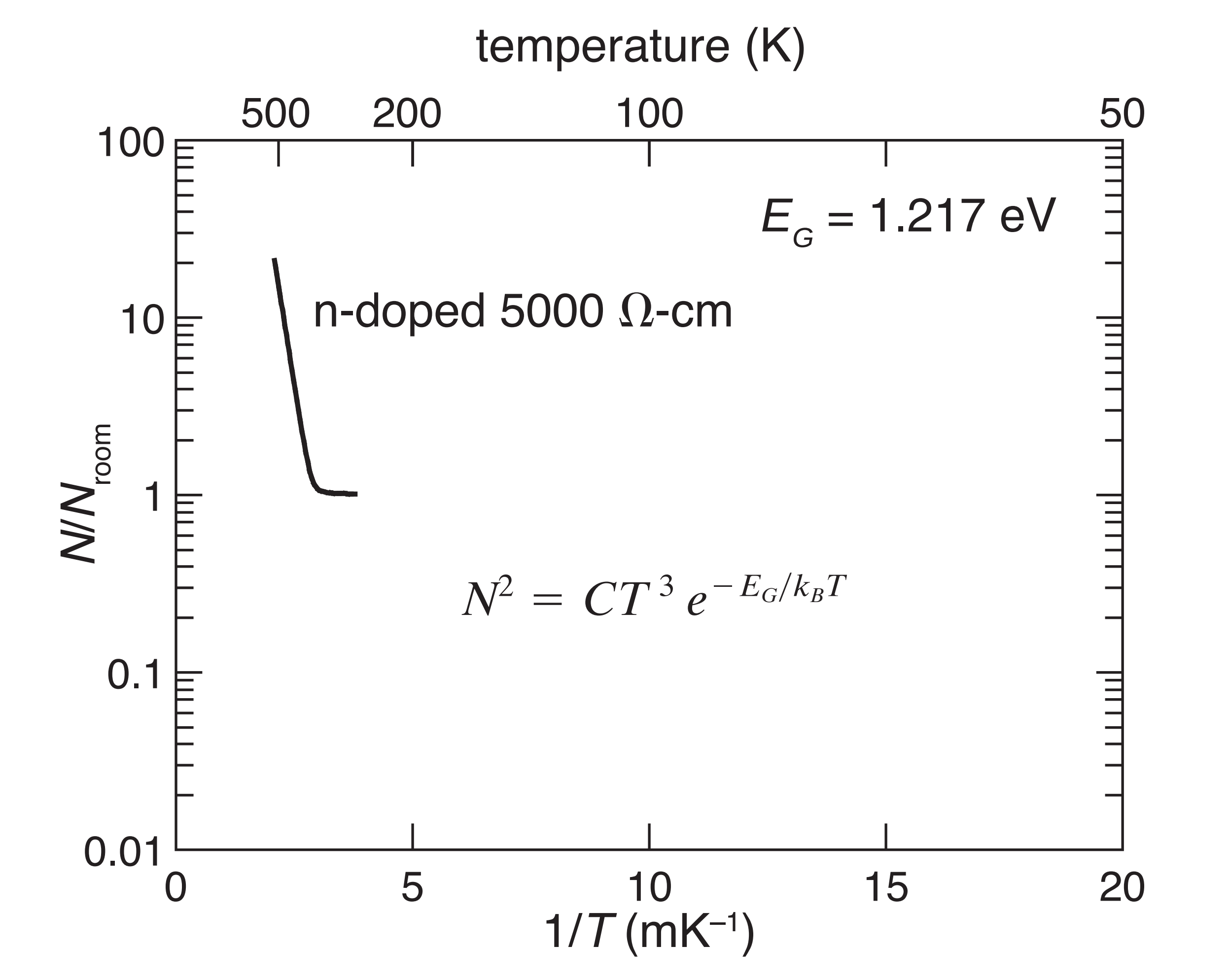

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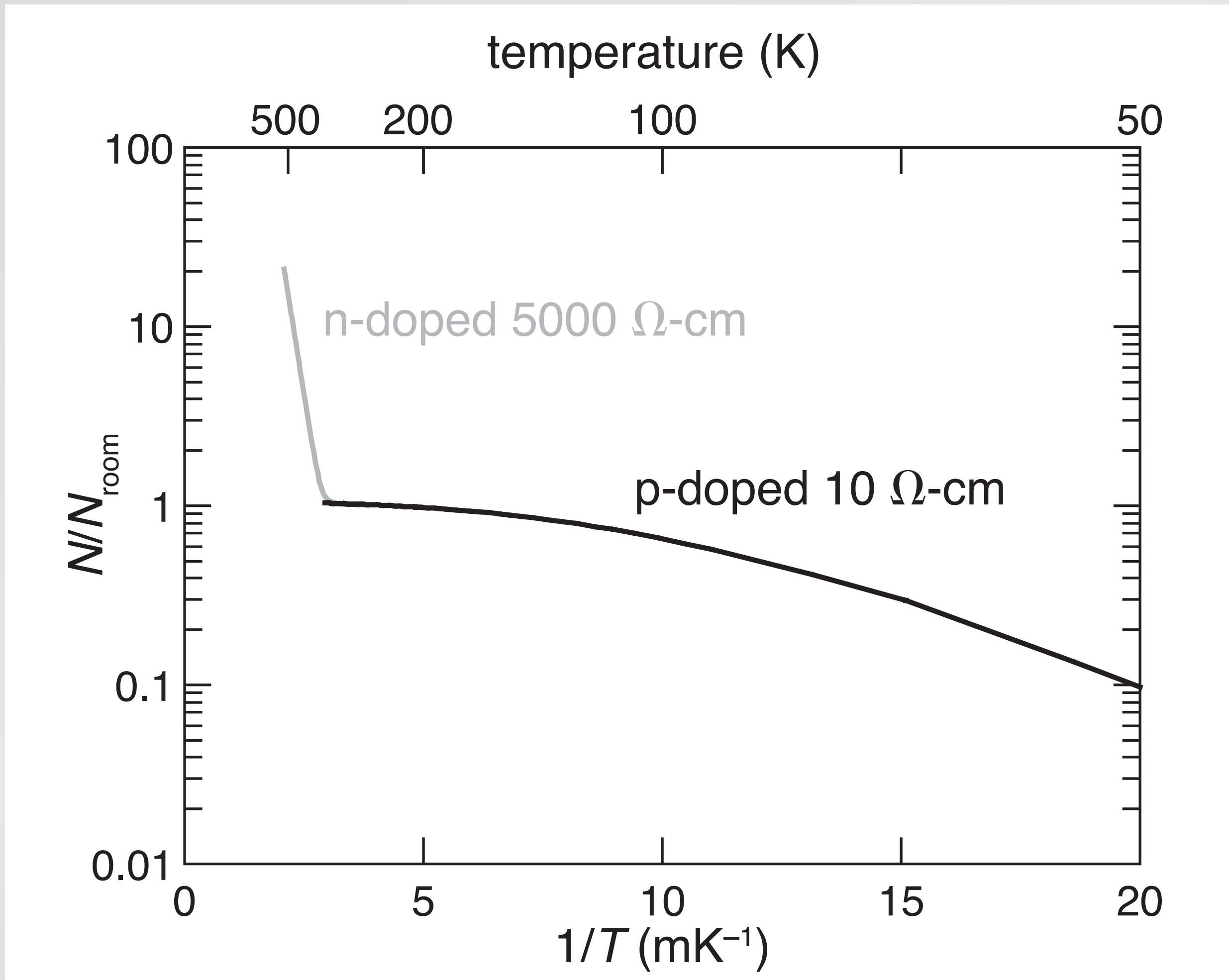

Optical hyperdoping

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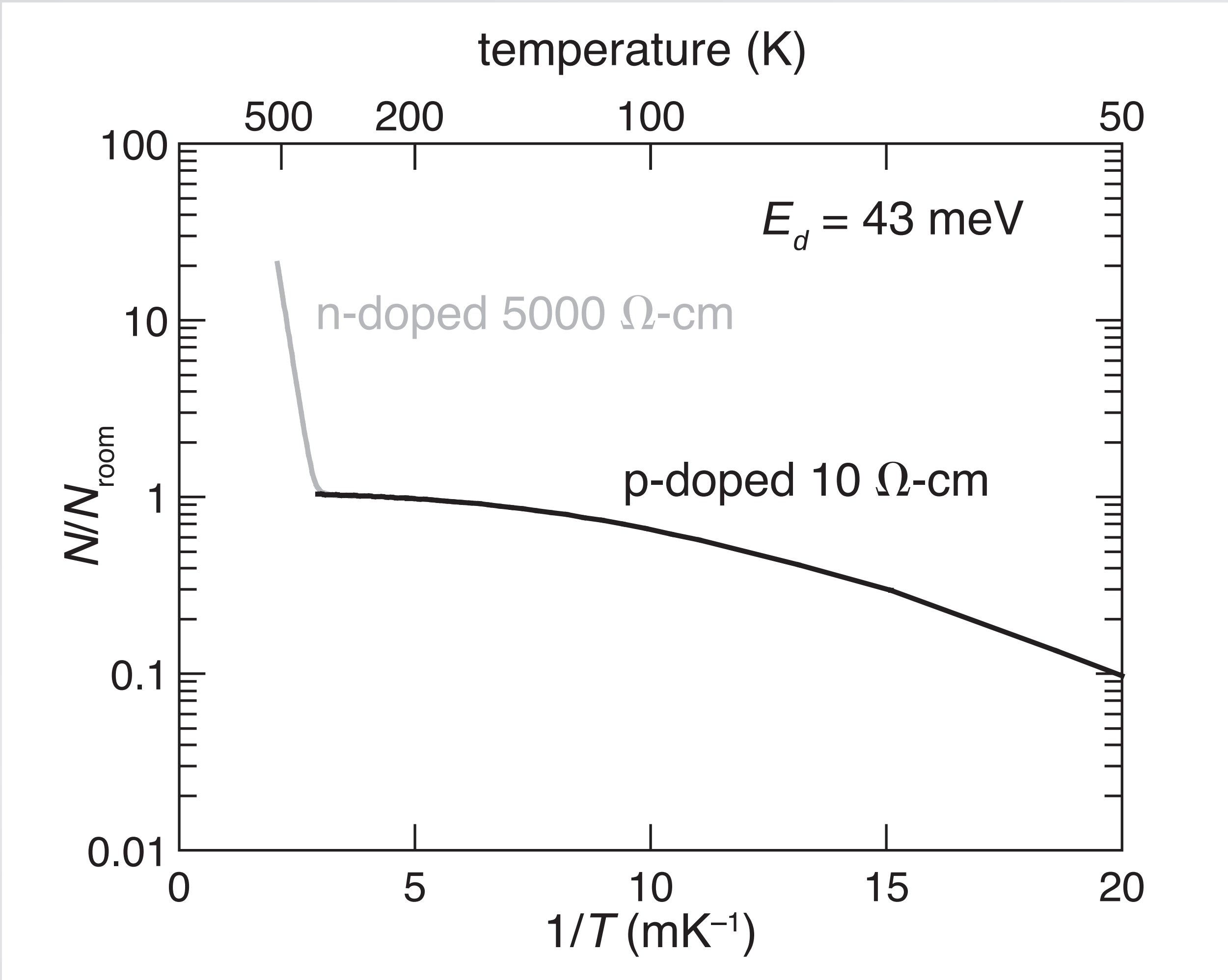

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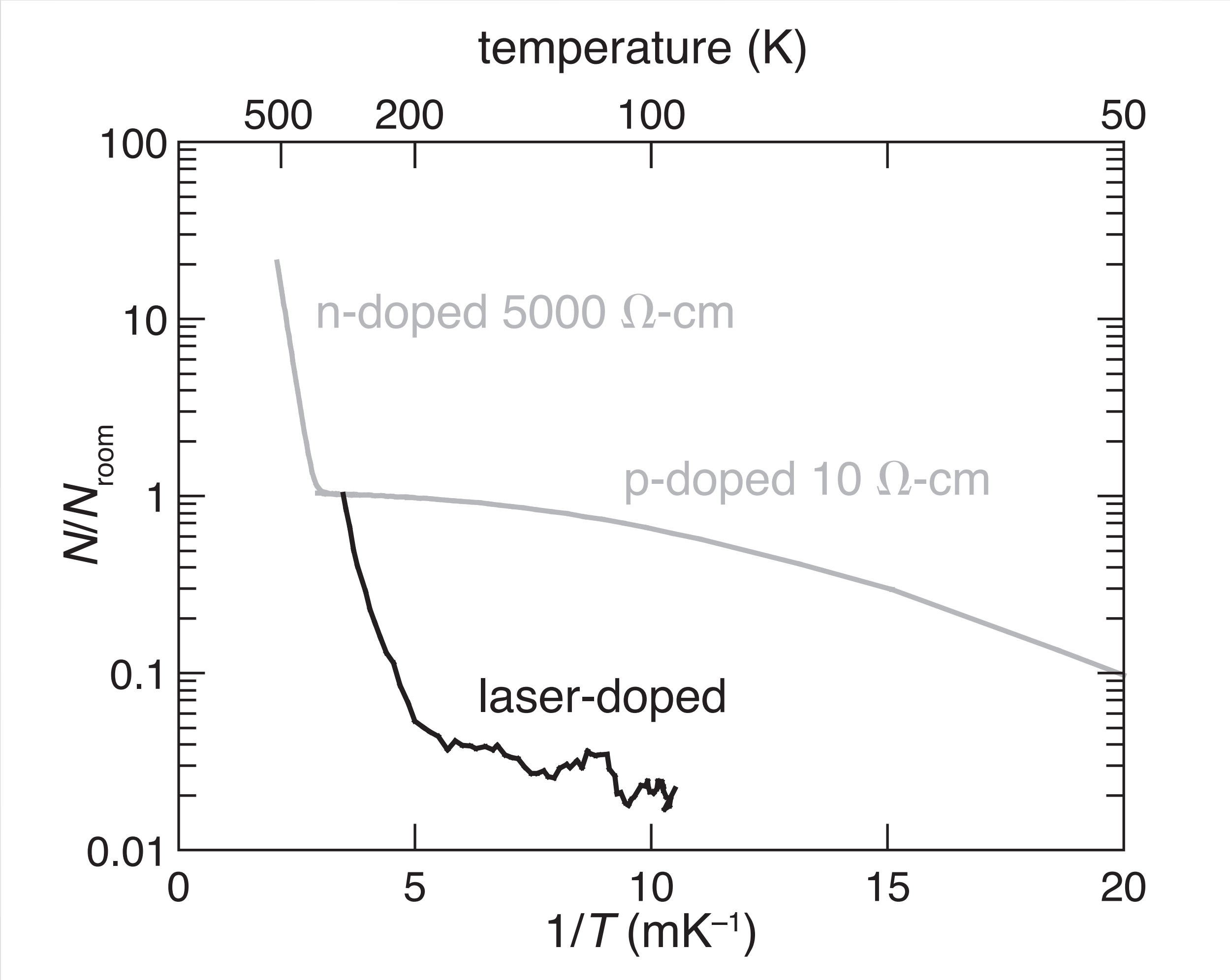

Optical hyperdoping

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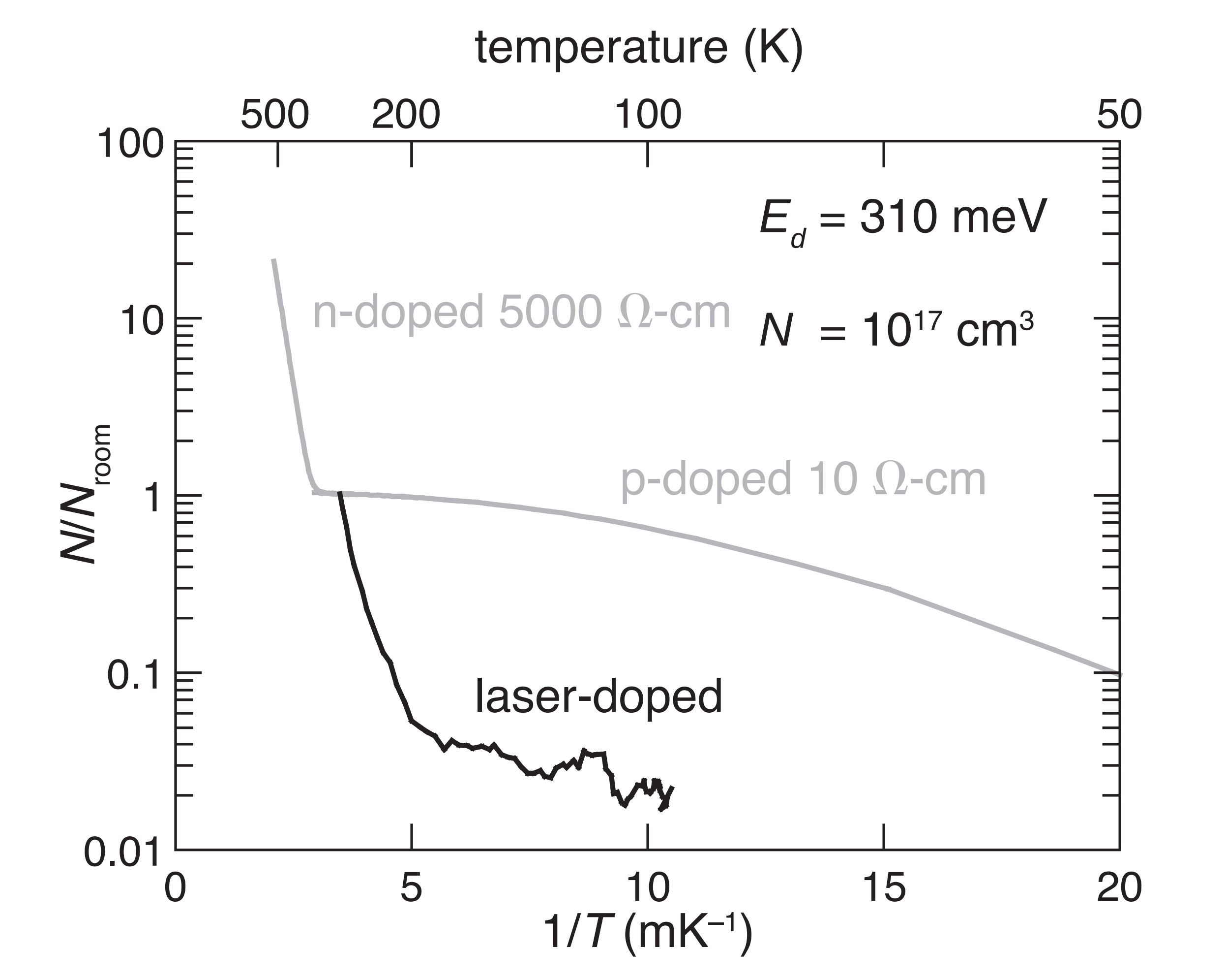
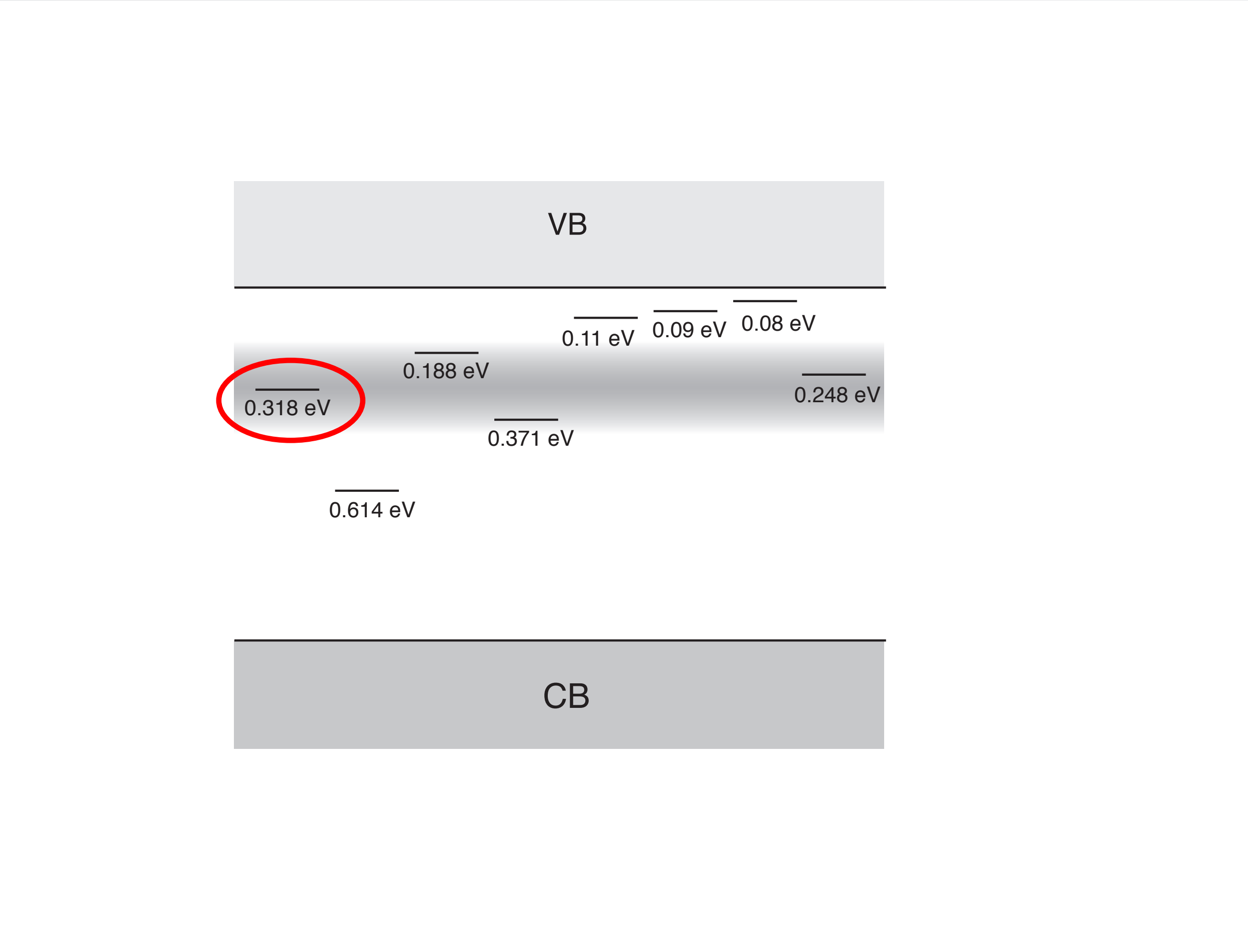


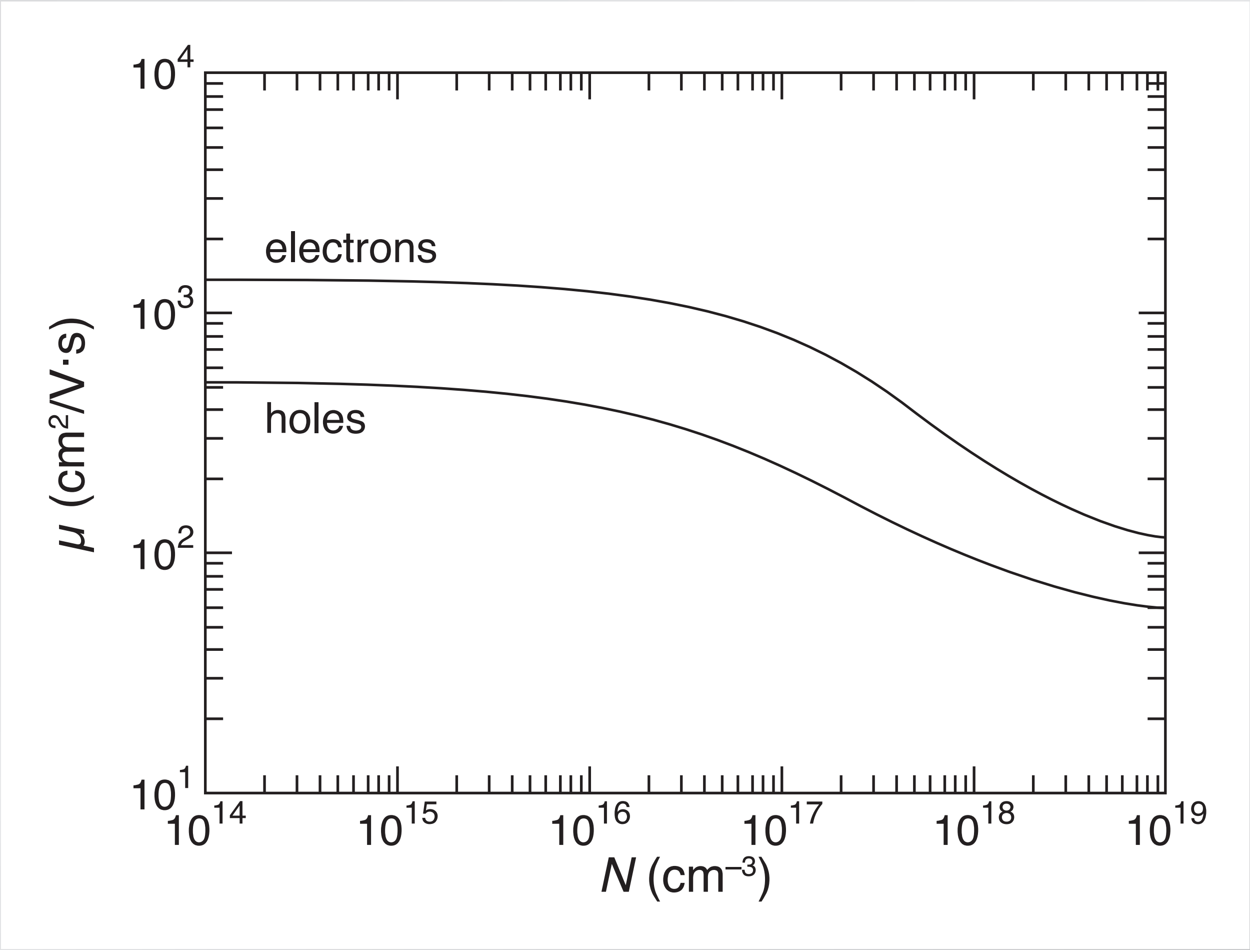
Optical hyperdoping

impurity (donor) band centered at 310 meV



Optical hyperdoping

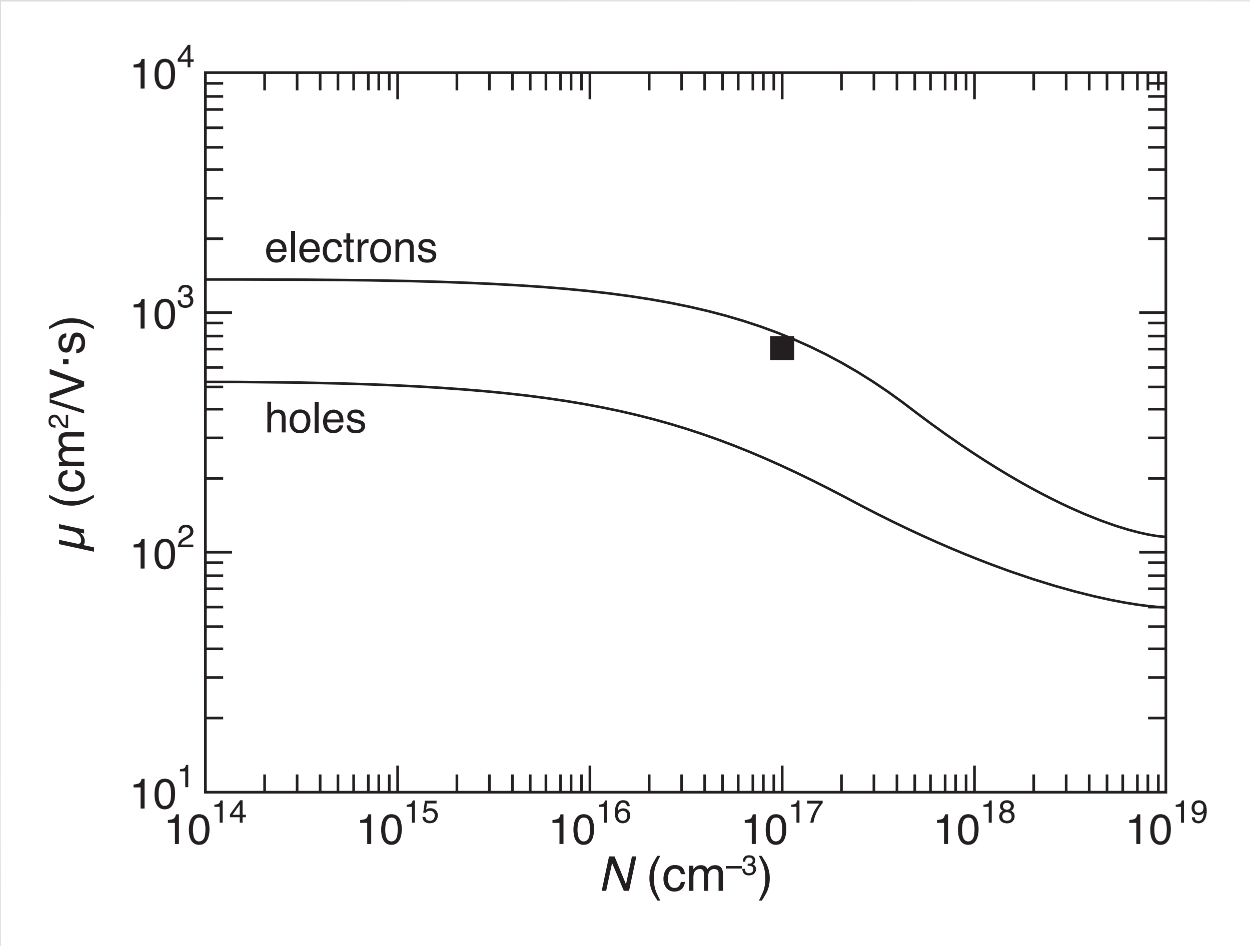
majority carrier mobility



Caughey *et al.*, Proc. IEEE 55, 2192 (1967)

Optical hyperdoping

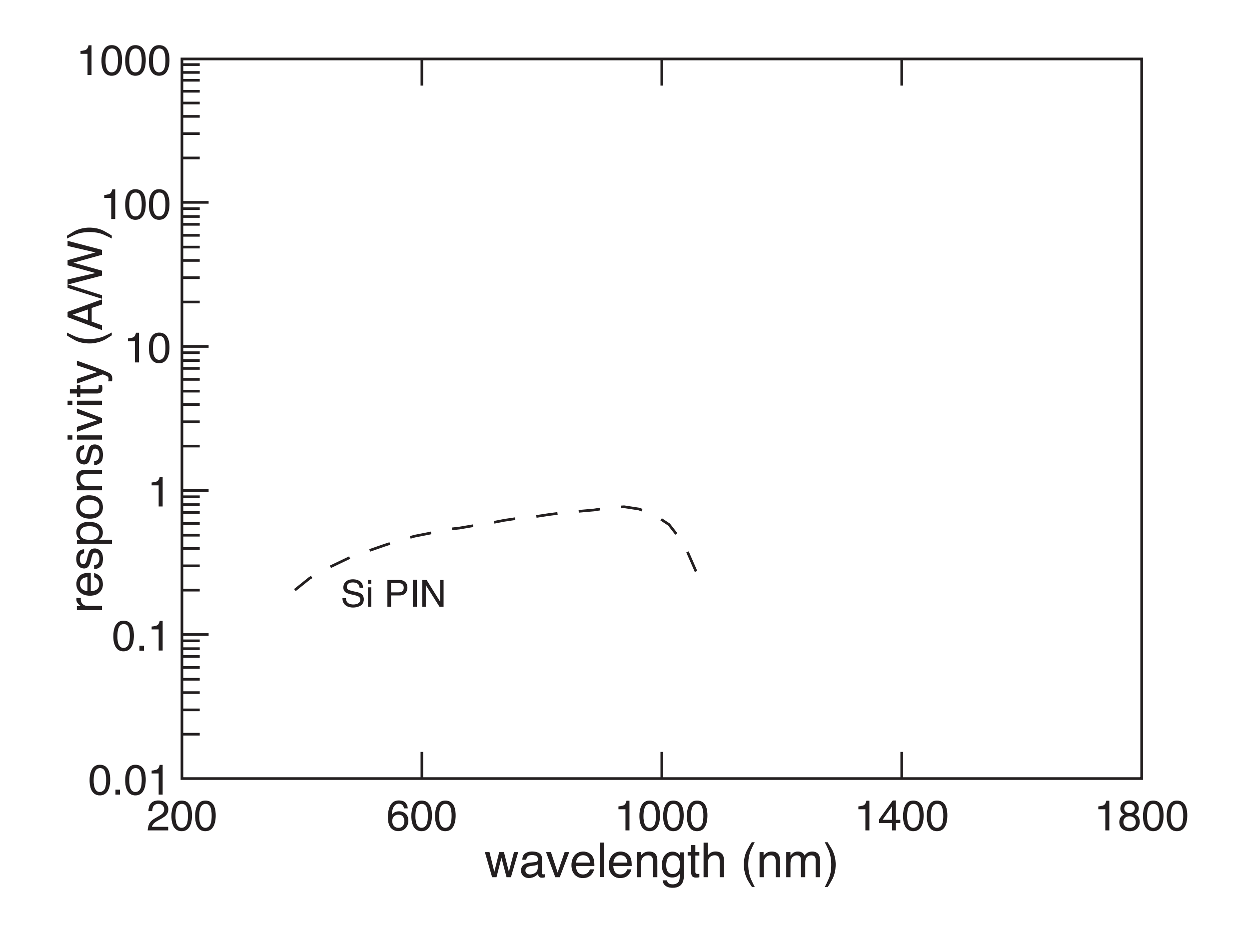
majority carrier mobility



Caughey *et al.*, Proc. IEEE 55, 2192 (1967)

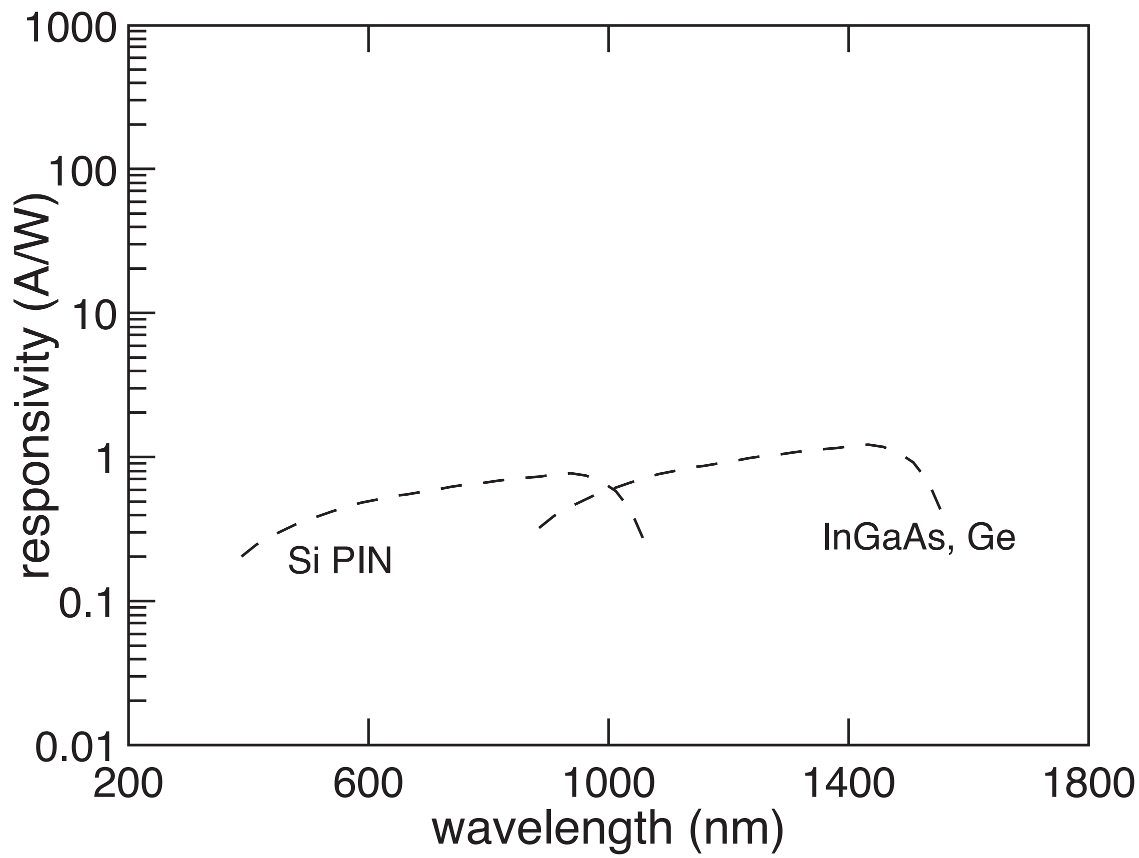
Optical hyperdoping

responsivity



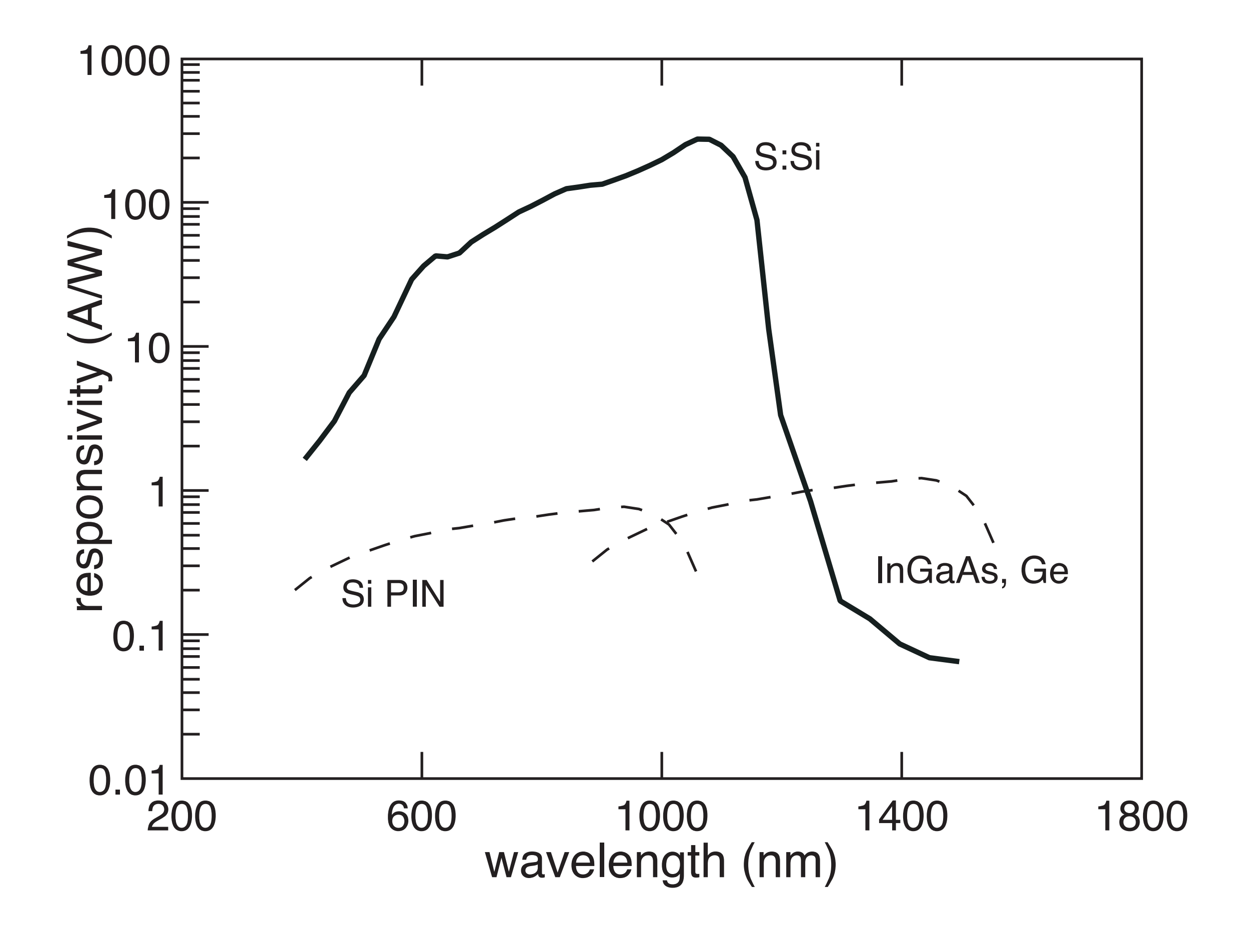
Optical hyperdoping

responsivity



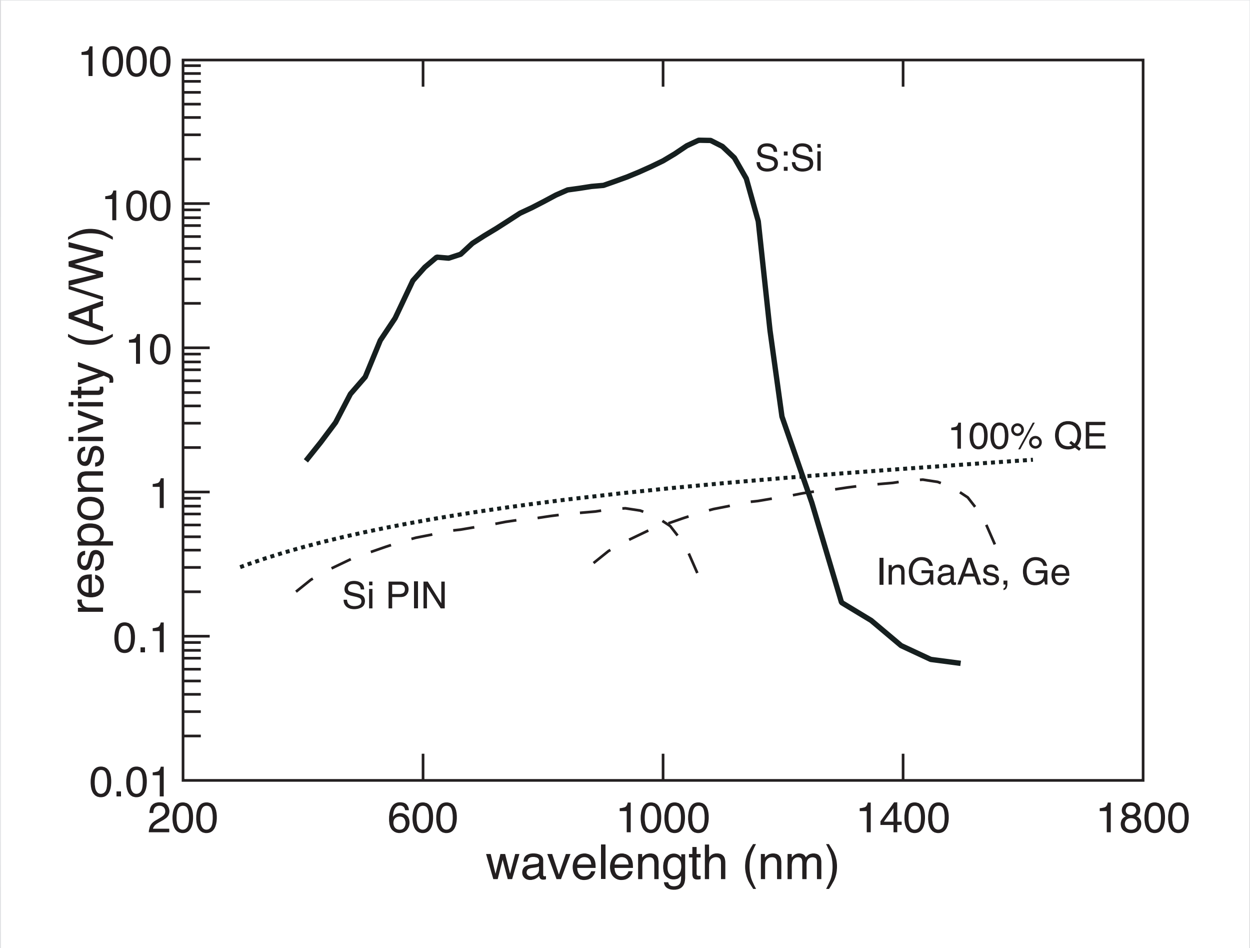
Optical hyperdoping

responsivity



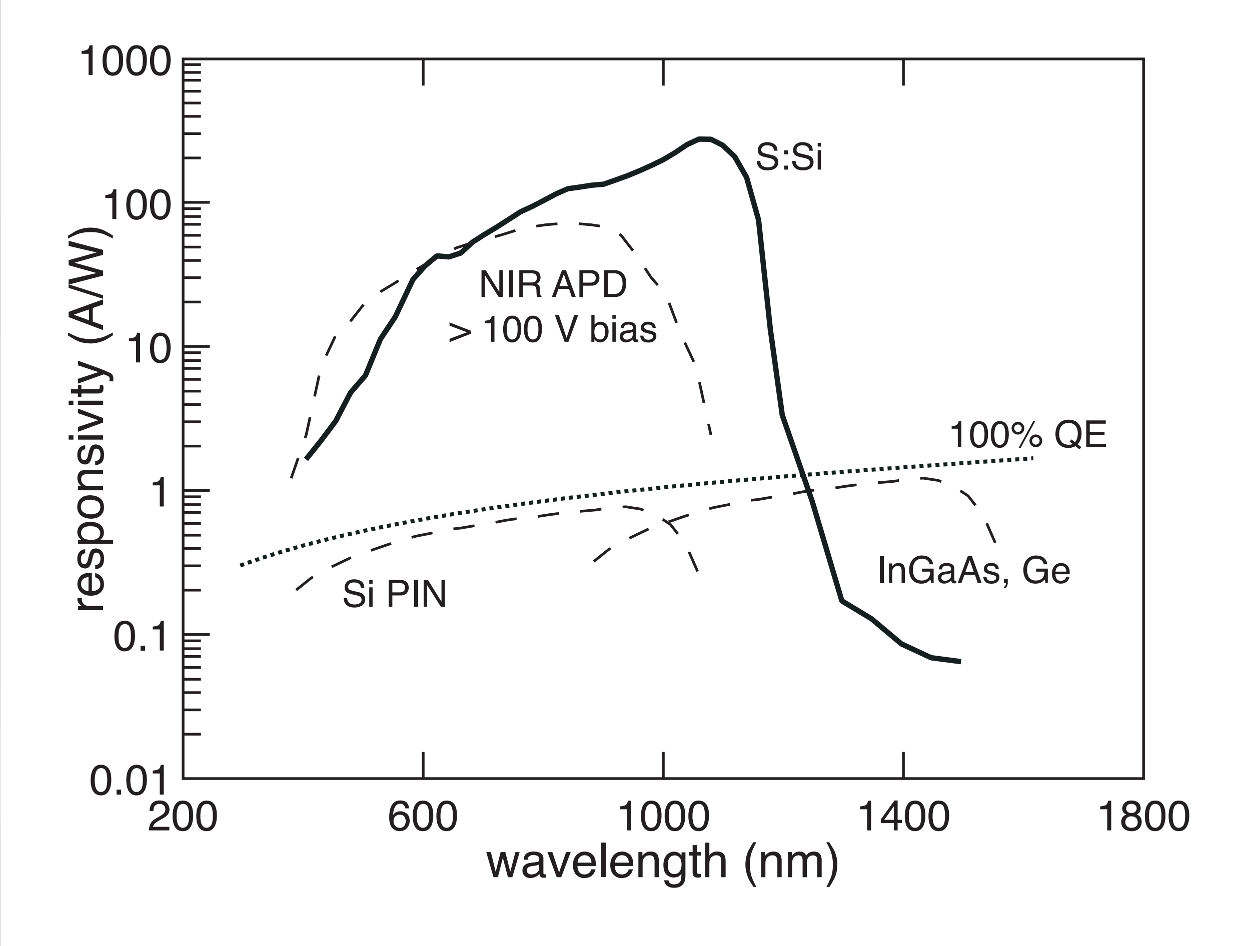
Optical hyperdoping

responsivity



Optical hyperdoping

responsivity

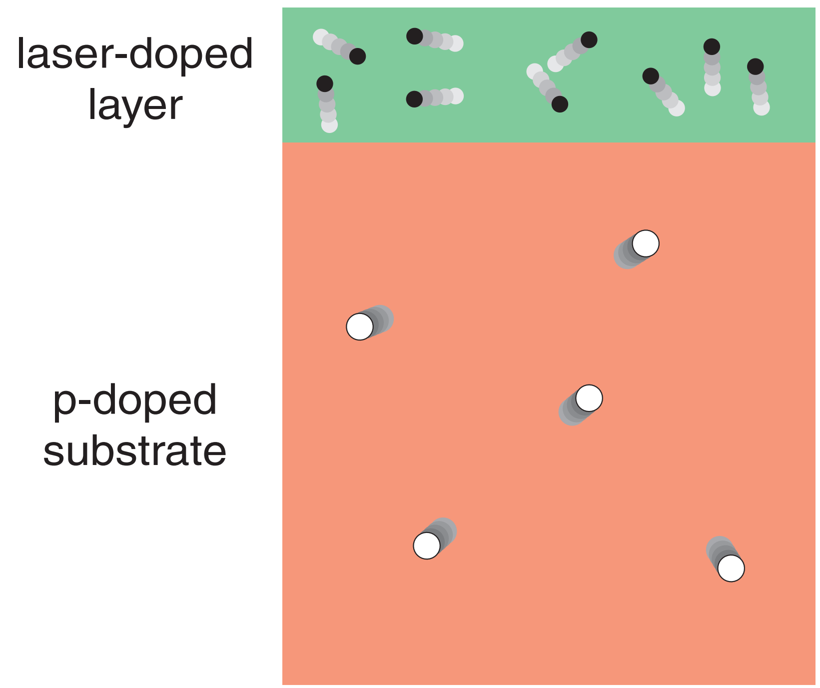


Optical hyperdoping

What causes gain?

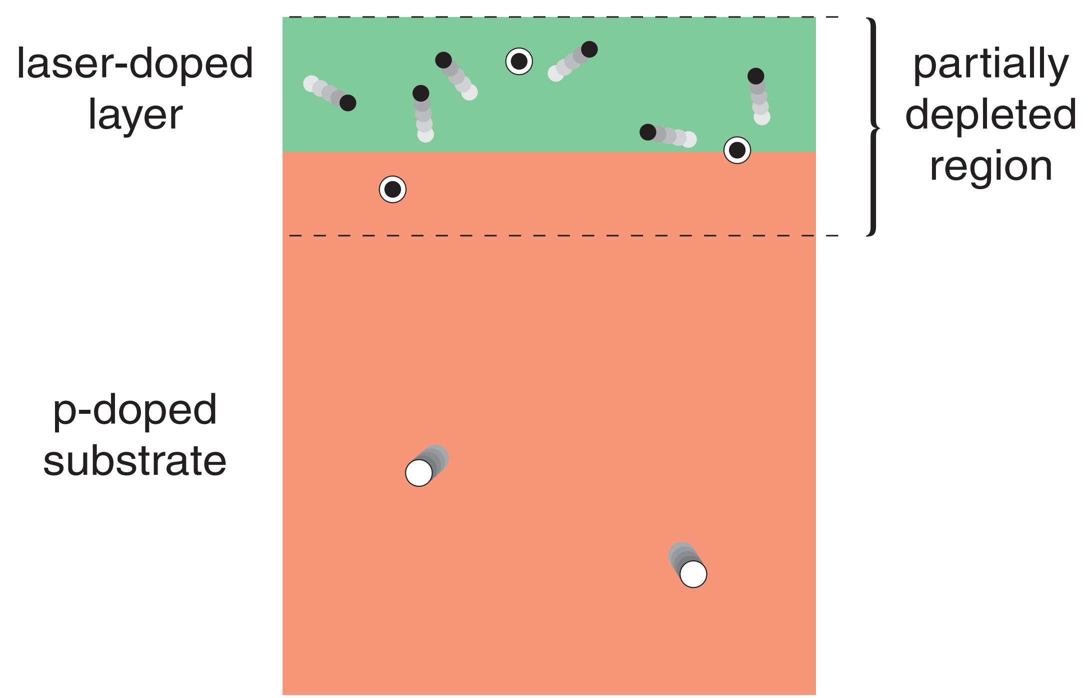
- **impact excitation (avalanching)**
- **carrier lifetime >> transit time (photoconductive gain)**
- **some other mechanism**

Optical hyperdoping



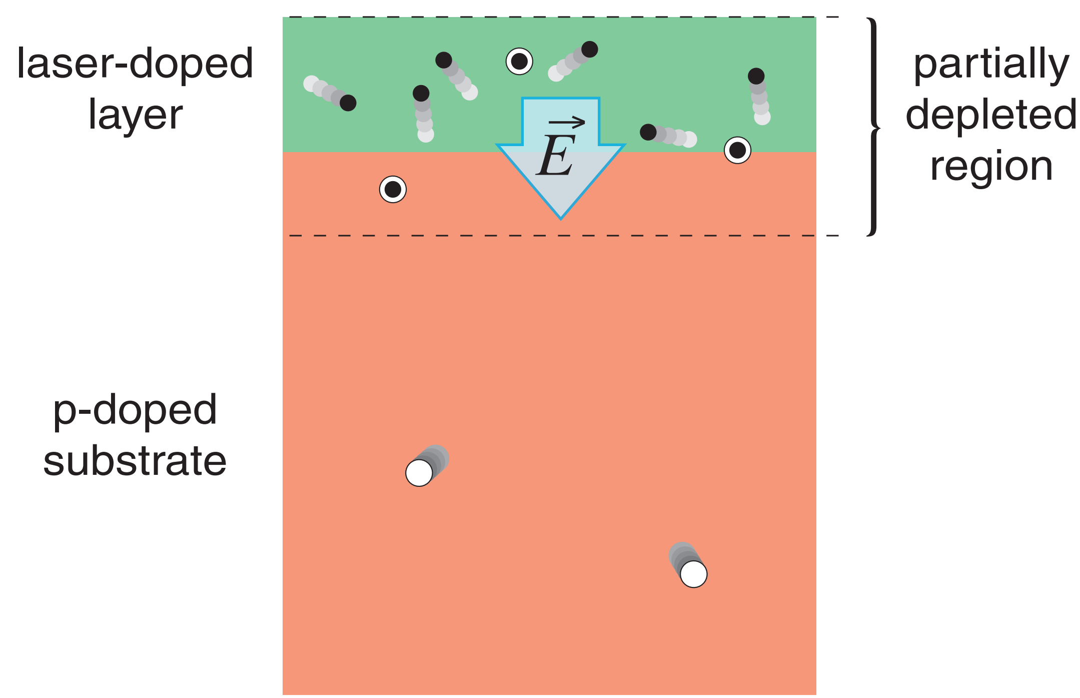
"pl junction"

Optical hyperdoping



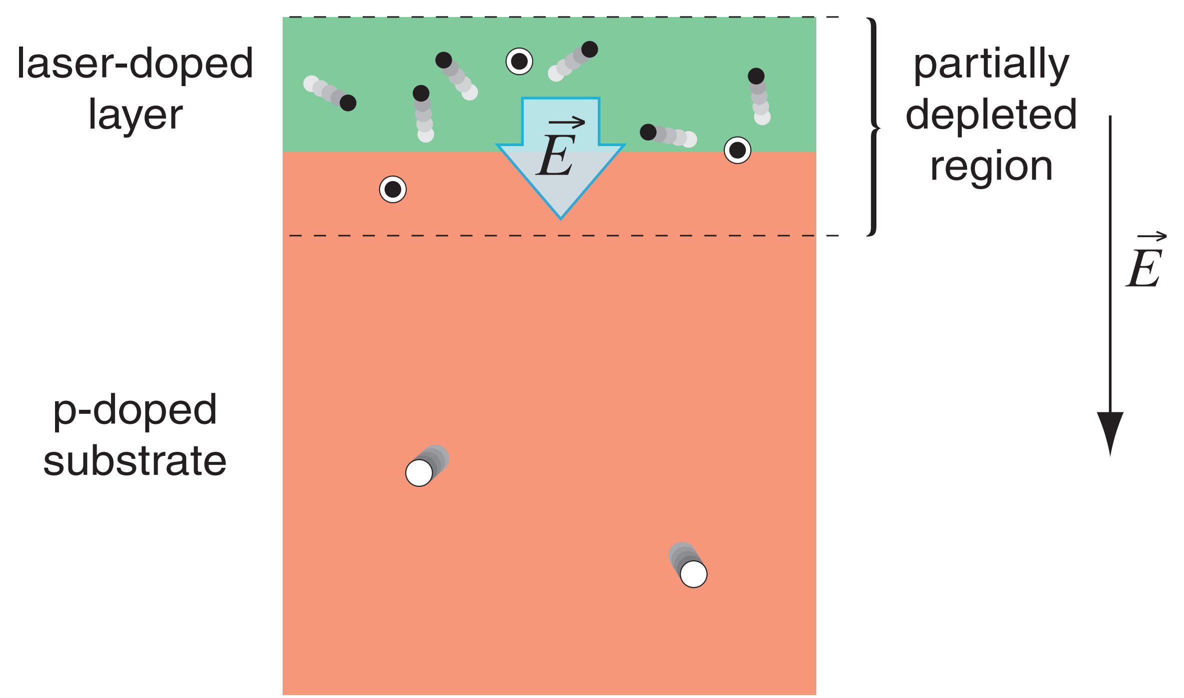
formation of partially depleted region

Optical hyperdoping



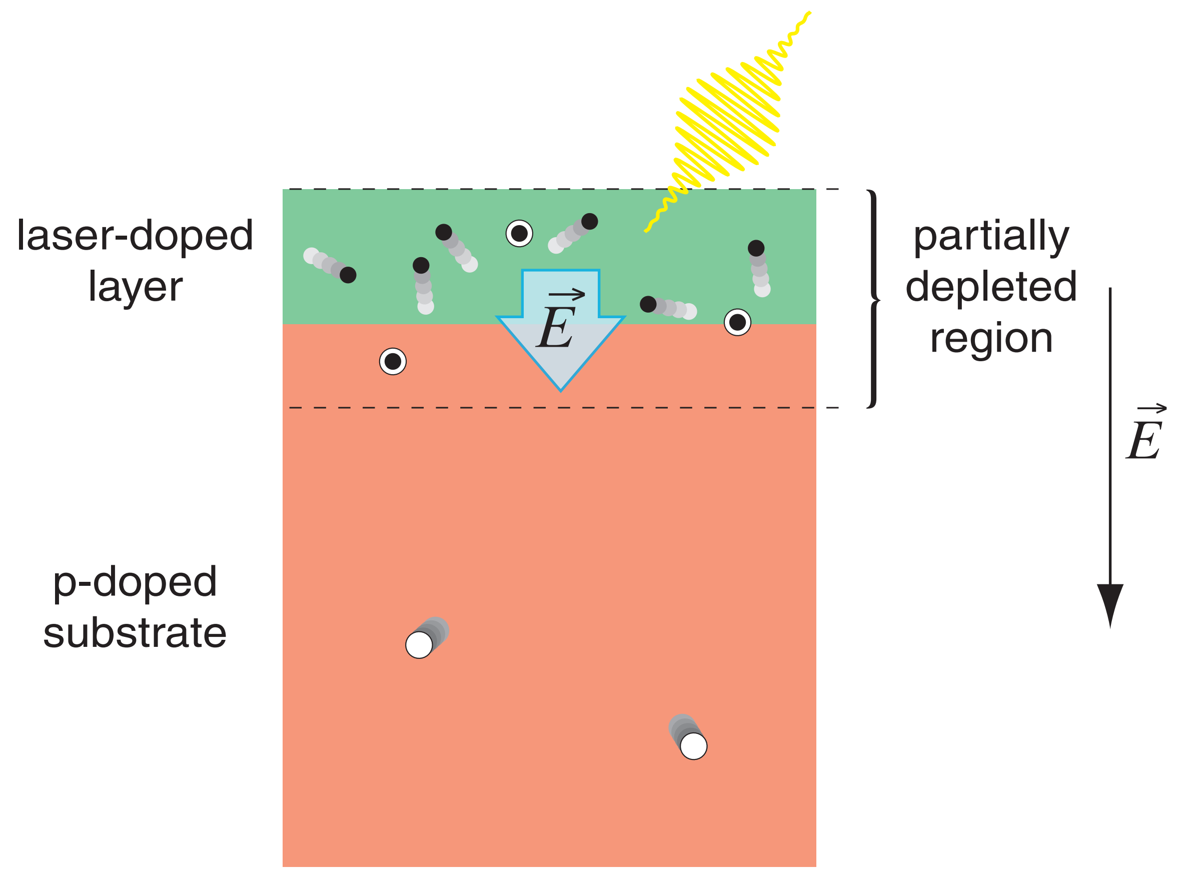
formation of partially depleted region

Optical hyperdoping



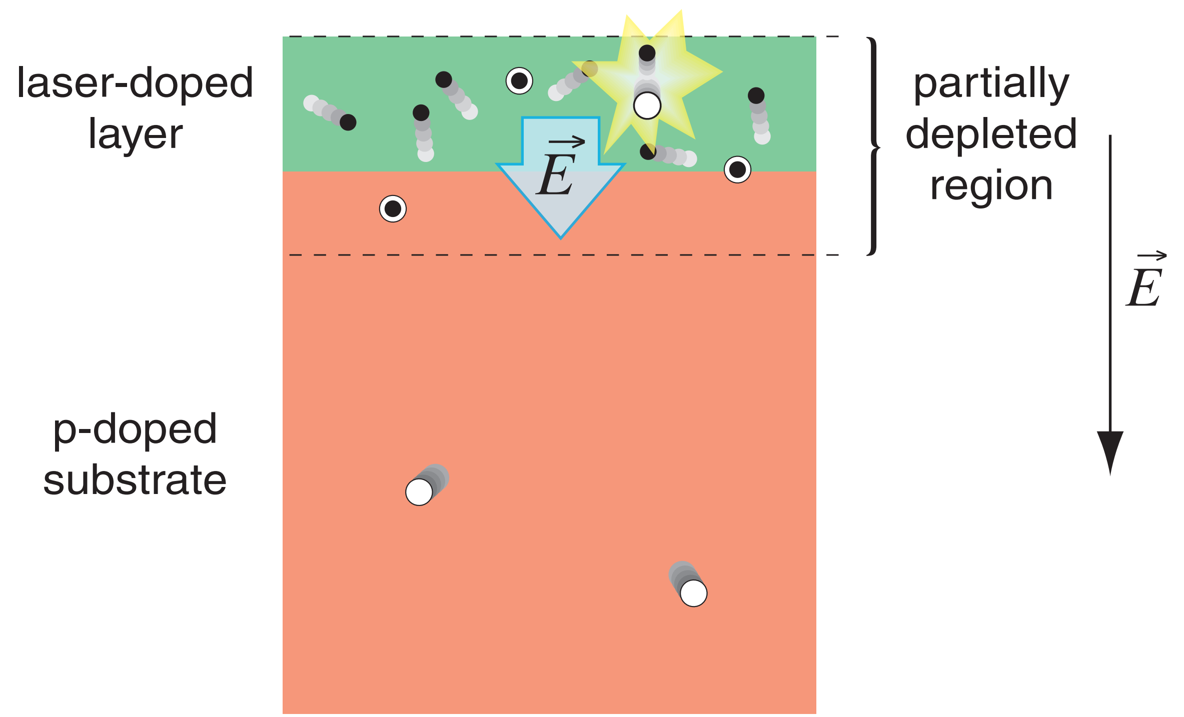
apply backward bias…

Optical hyperdoping



…incident photon generates electron-hole pair…

Optical hyperdoping



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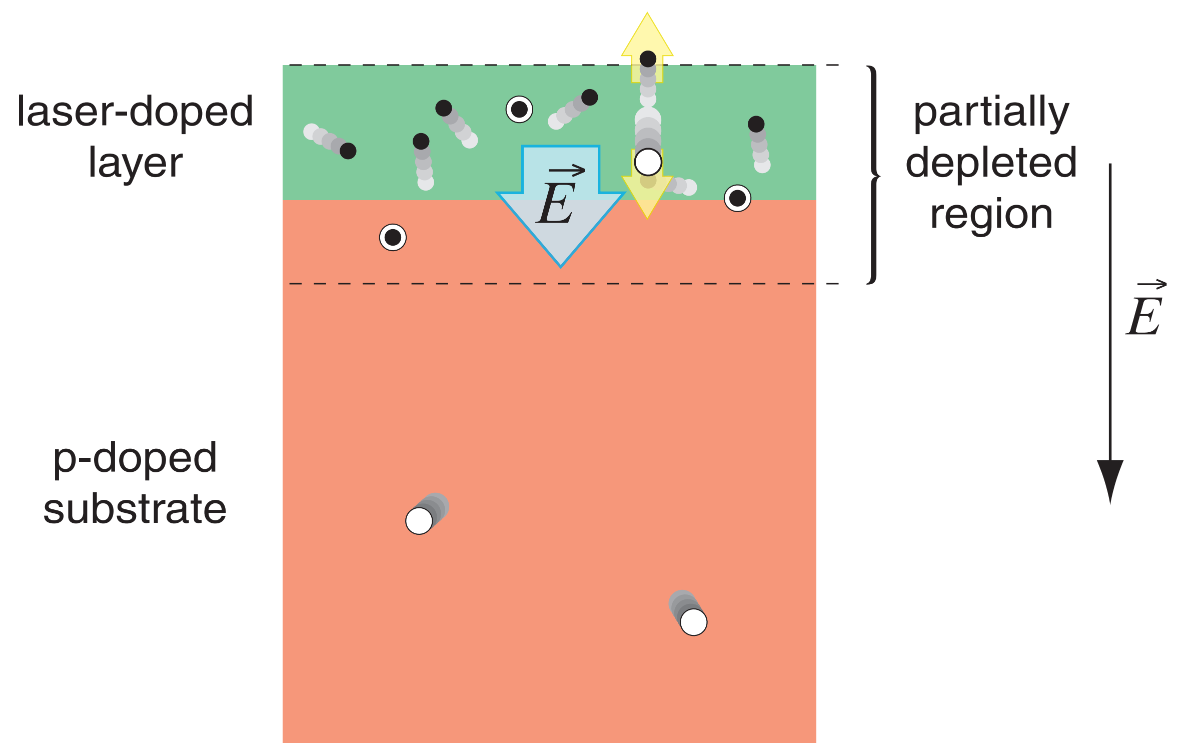
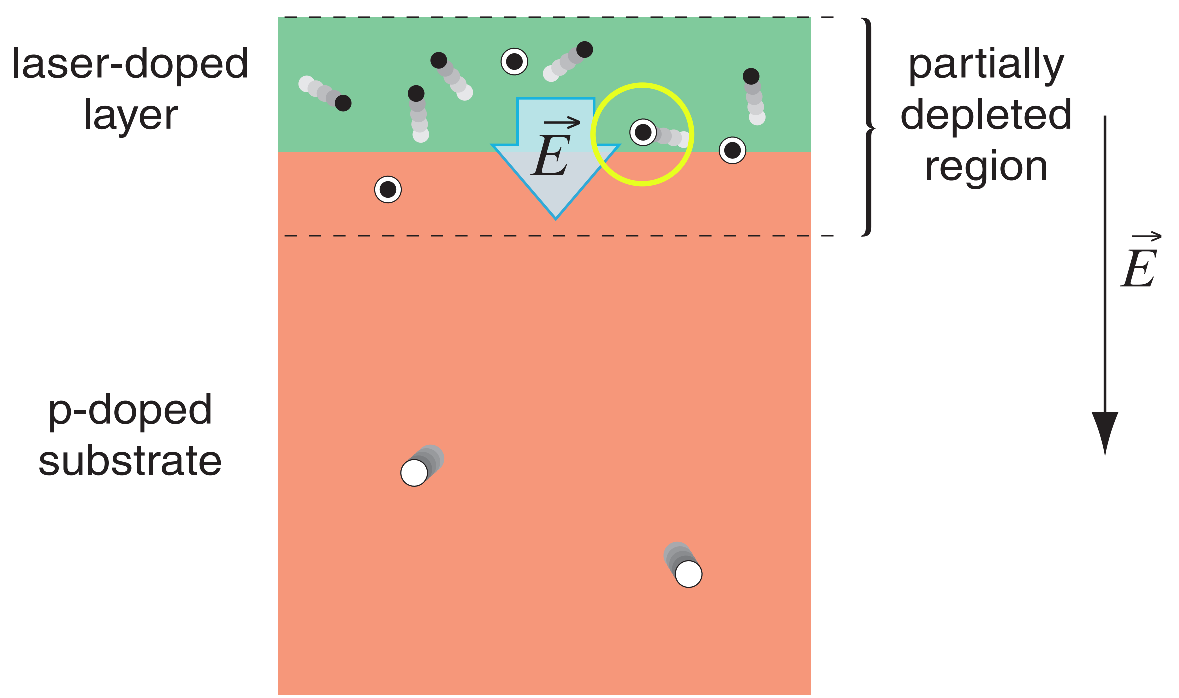


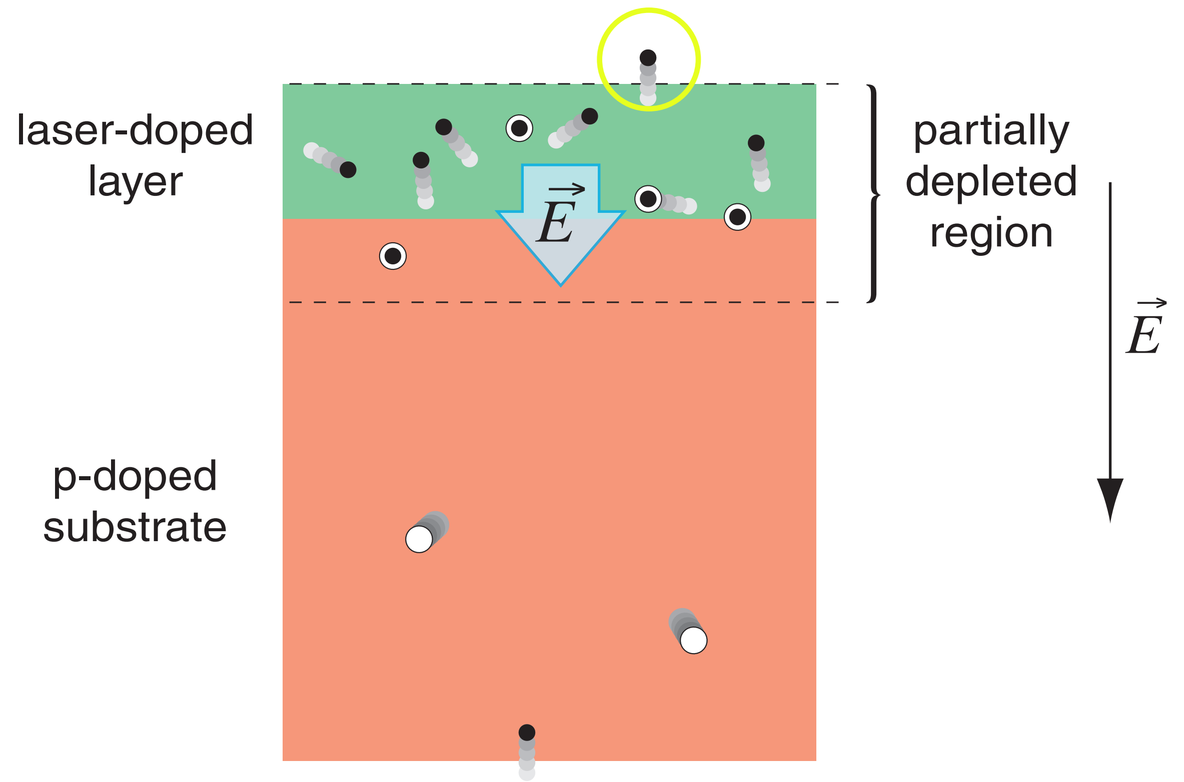
…carriers accelerate away from each other…

Optical hyperdoping



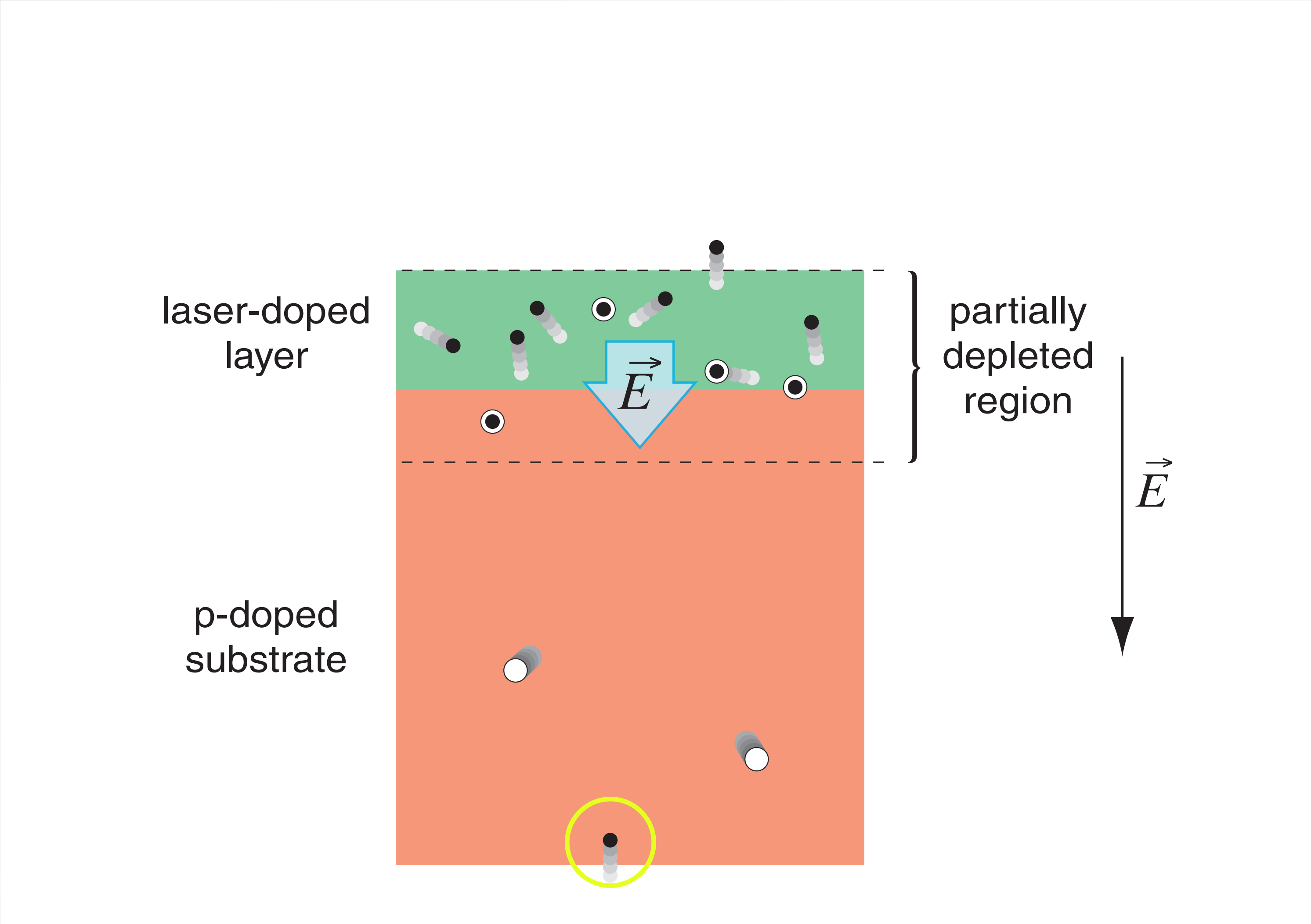
...hole is trapped

Optical hyperdoping



meanwhile electron exits sample…

Optical hyperdoping



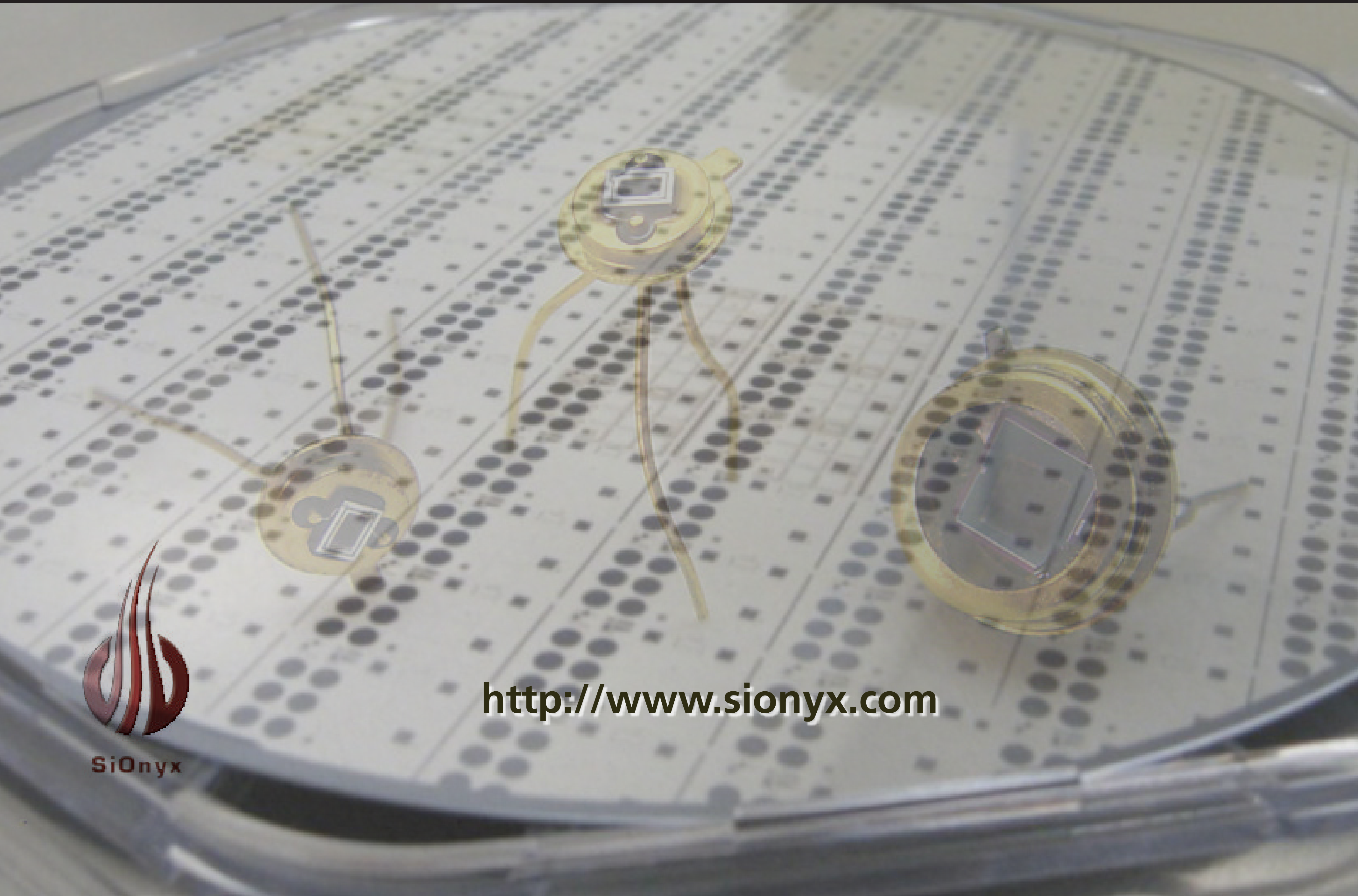
...and source provides new electron

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:

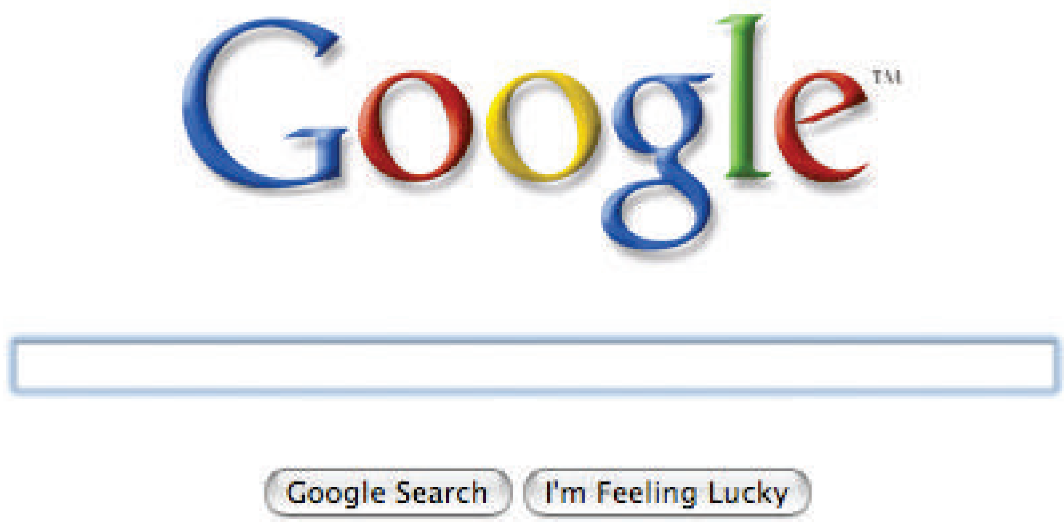
- inclusion during growth
- thermal diffusion
- ion implantation

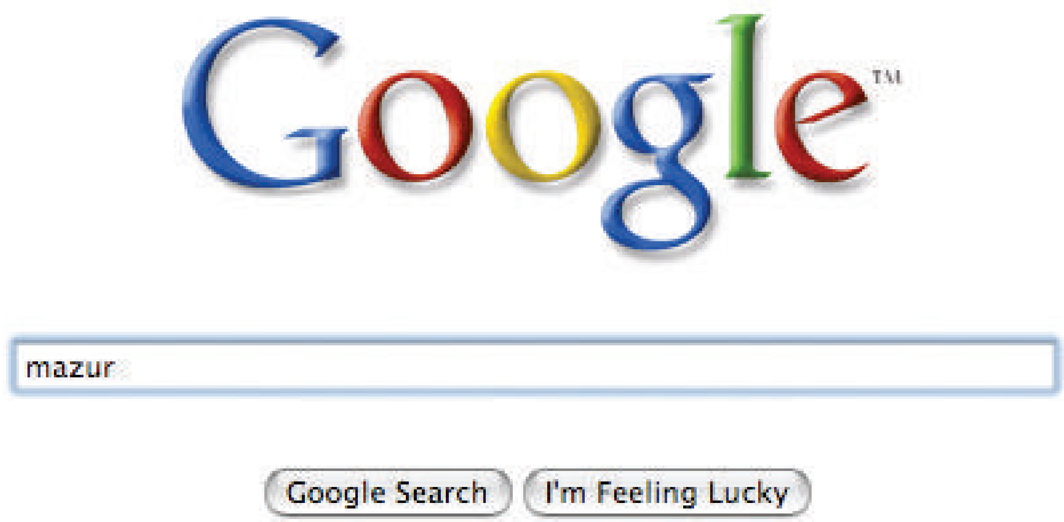
Funding:

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
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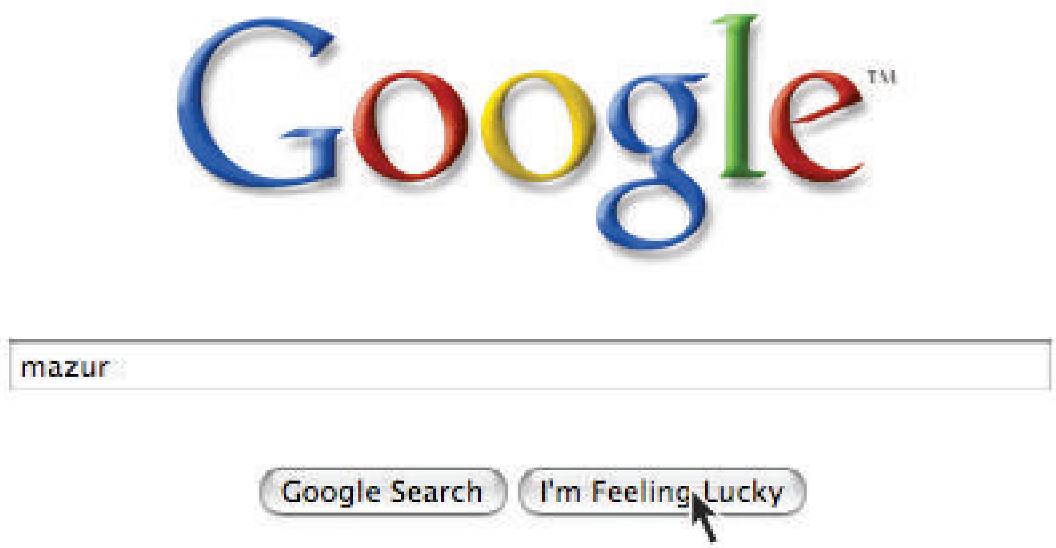
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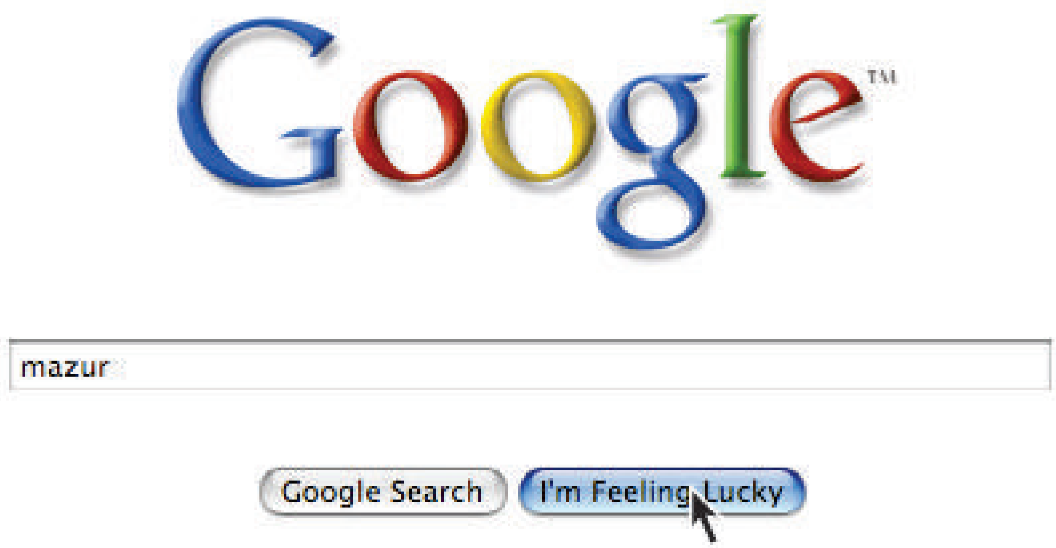
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