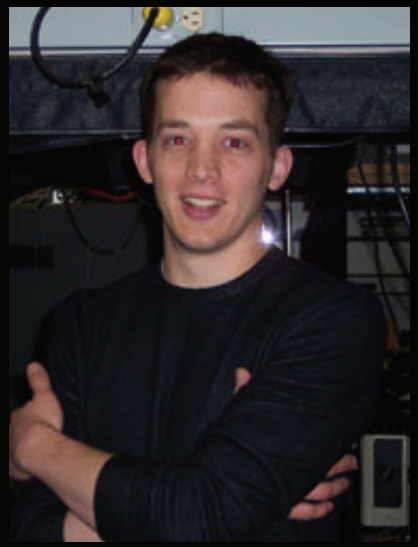
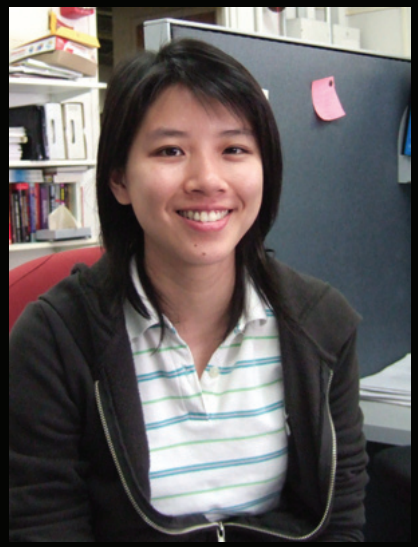
Black silicon: Engineering an intermediate band in silicon for optical sensing and photovoltaics

G1 Faculty Lecture
Harvard University
Cambridge, MA, 8 November 2010



Mark Winkler

Renee Sher



Yu-Ting Lin

Eric Mazur

and also....

Eric Diebold
Haifei Albert Zhang
William Whitney
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

Dr. John Chervinsky
Dr. Joshua Levinson

Prof. Michael Aziz
Prof. Cynthia Friend
Prof. Howard Stone

Prof. Tonio Buonassisi (MIT)
Prof. Silvija Gradecak (MIT)
Dr. Bonna Newman (MIT)
Joe Sullivan (MIT)
Matthew Smith (MIT)

Prof. Augustinus Asenbaum (Vienna)

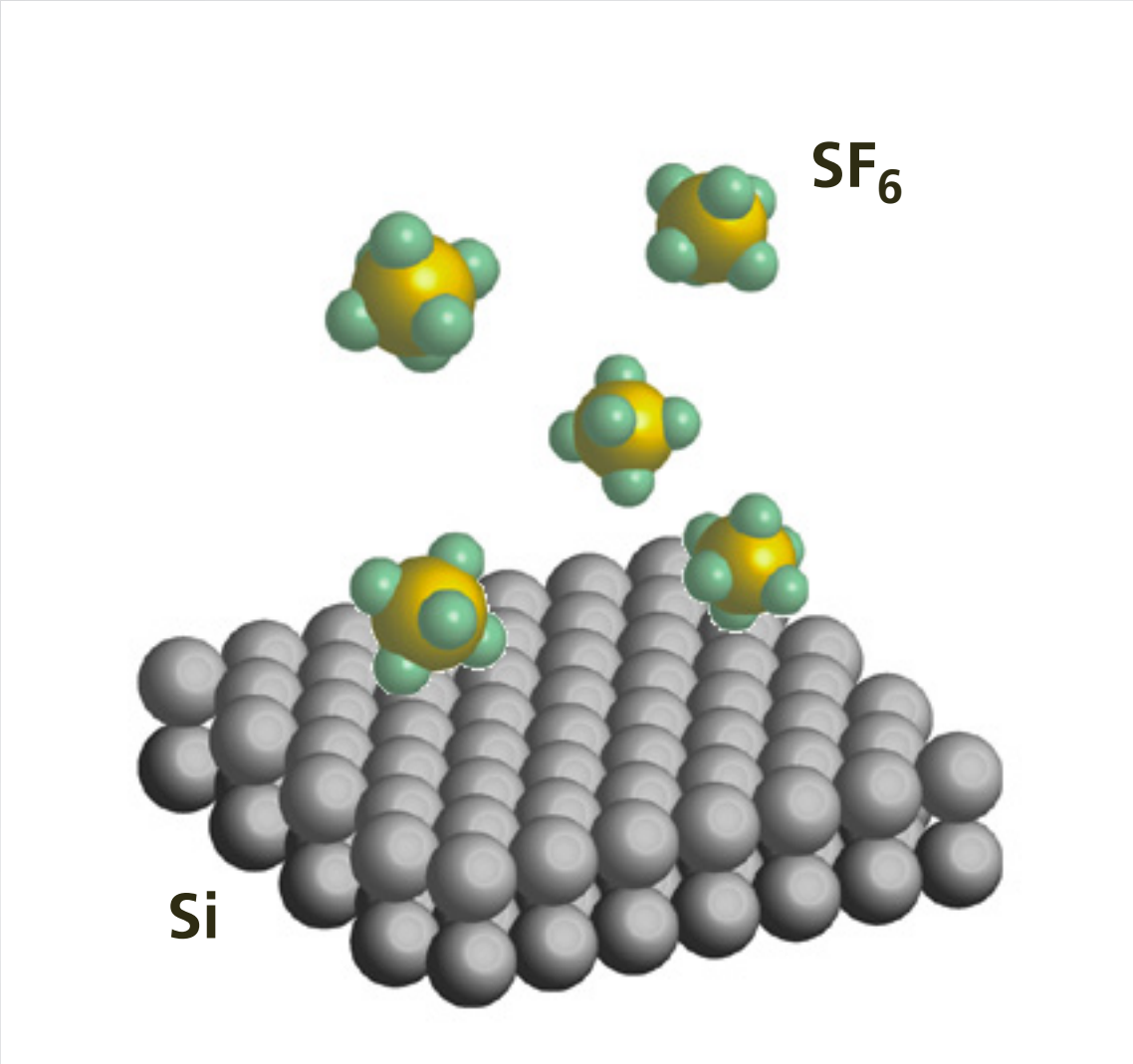
Dr. François Génin (LLNL)
Mark Wall (LLNL)

Dr. Richard Farrell (RMD)
Dr. Arieh Karger (RMD)
Dr. Richard Meyers (RMD)

Dr. Pat Maloney (NVSED)

Dr. Jeffrey Warrander (ARDEC)

Introduction

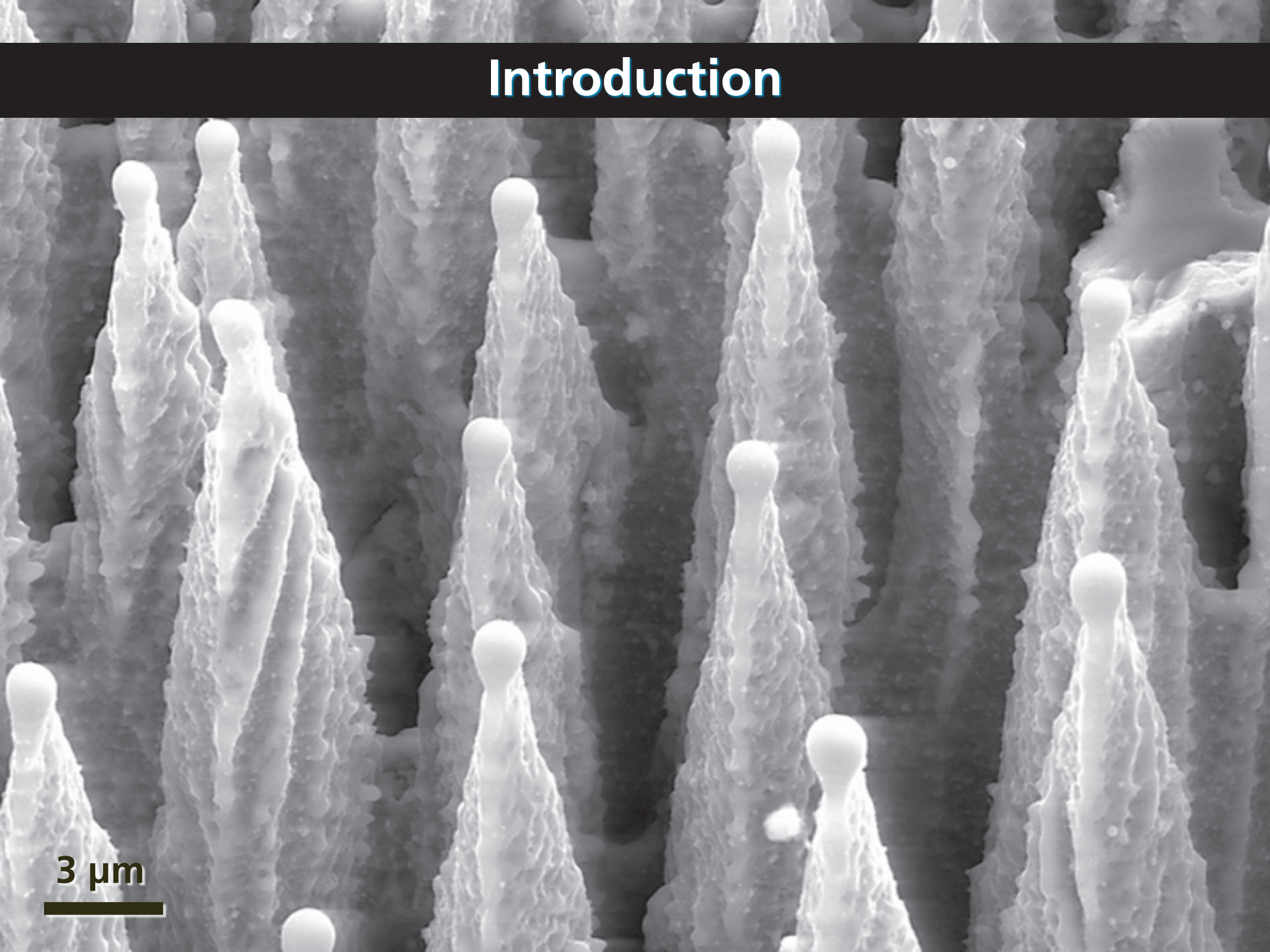


irradiate with 100-fs 10 kJ/m^2 pulses

Introduction

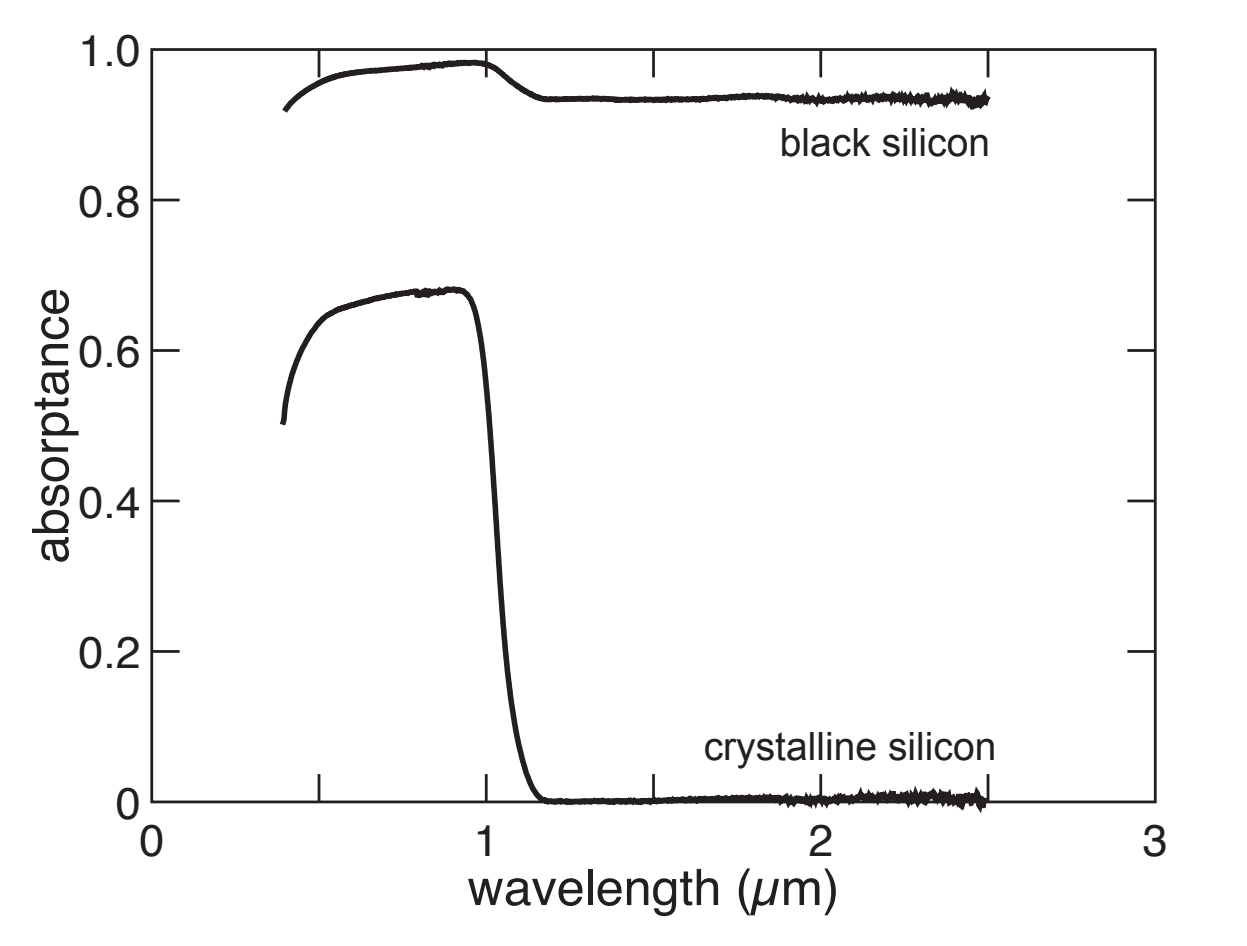
“black silicon”

Introduction



Introduction

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



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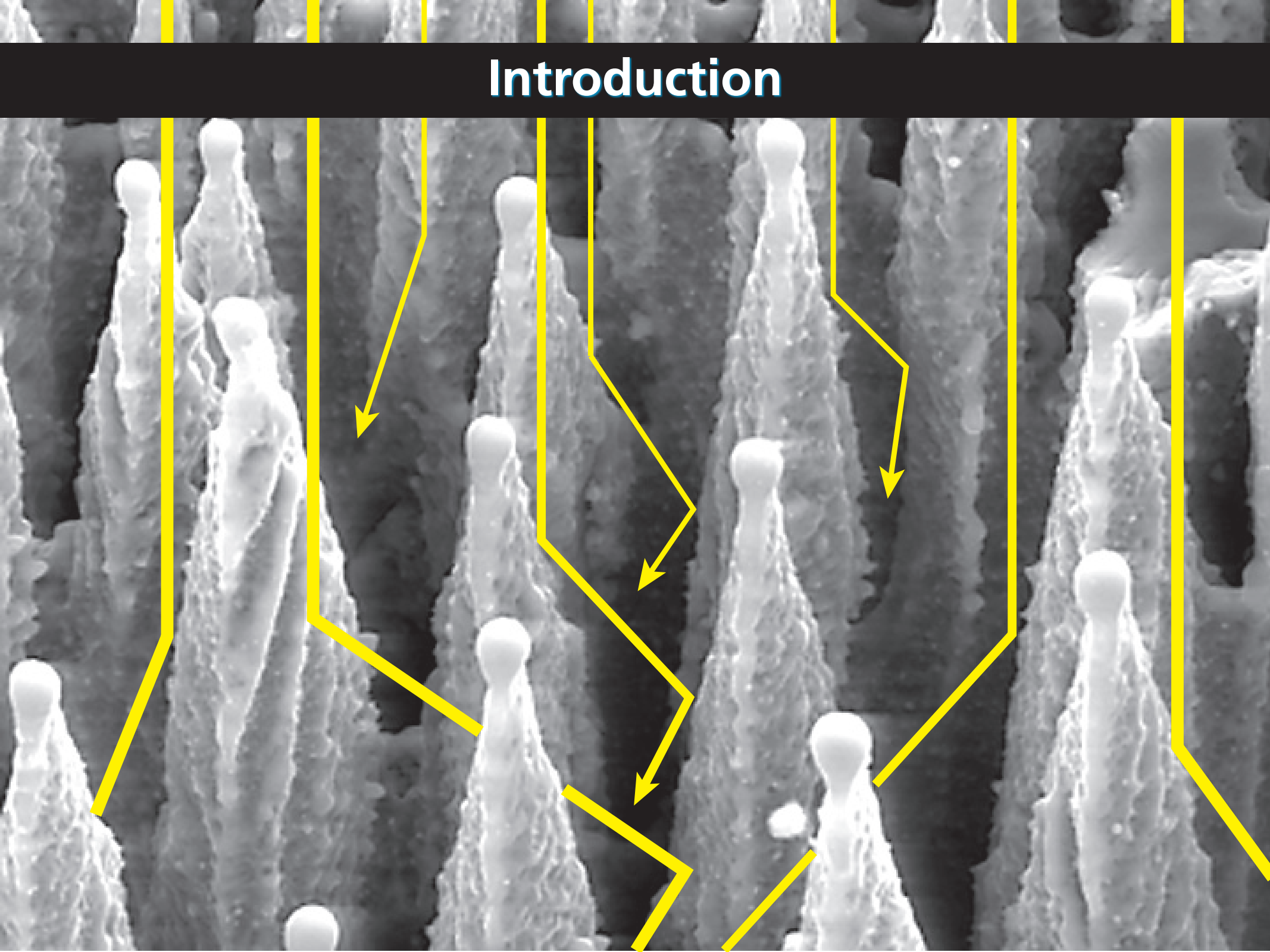

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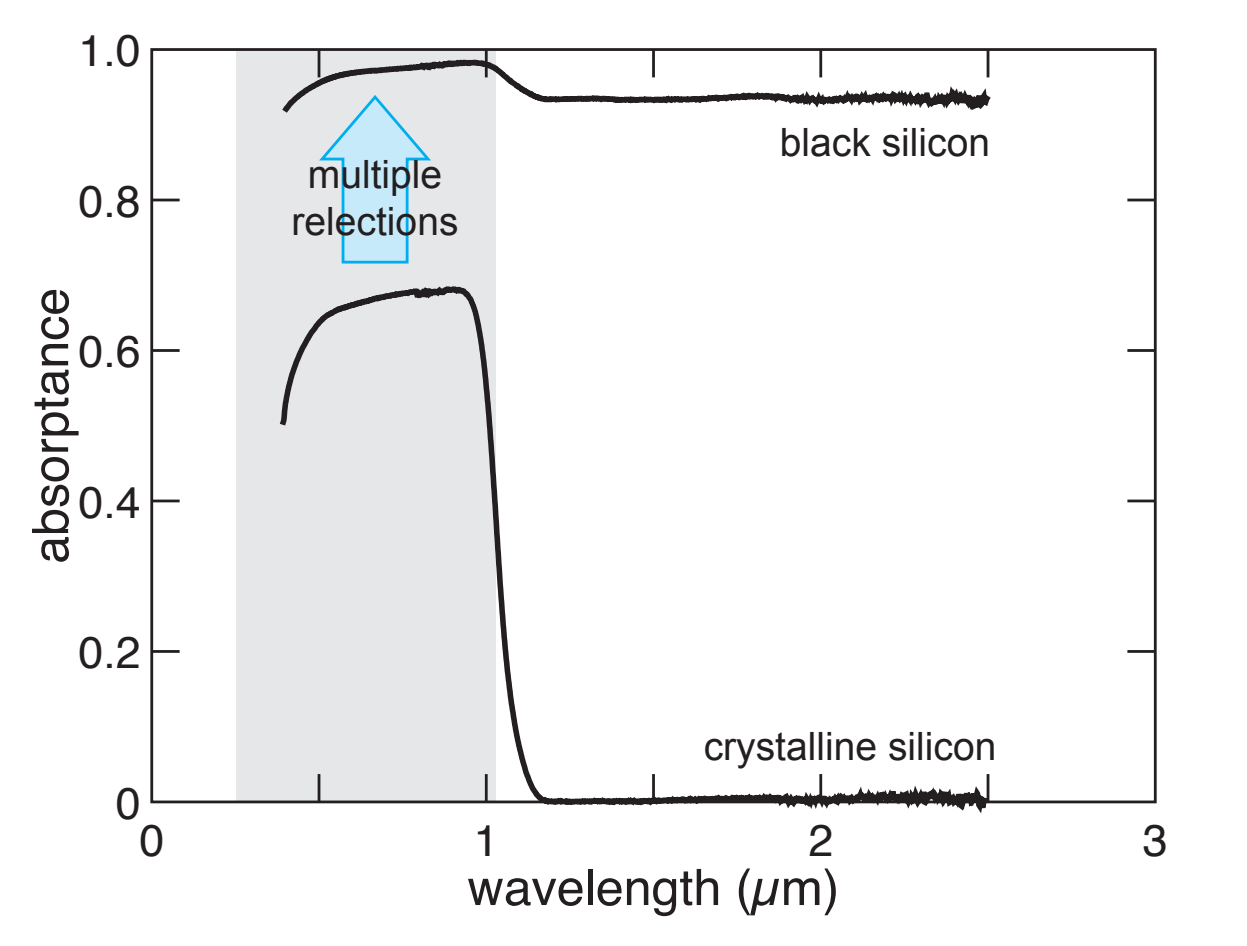

Introduction

band structure changes: defects and/or impurities

Introduction

a decade of research

OPTICAL	ELECTRONIC	STRUCTURAL
UV-VIS-NIR	Hall measurements	SEM
FTIR	conductivity	TEM
photoluminescence	IV rectification	EDX
PTD spectroscopy	c-AFM	SAD
UPS		EXAFS
XPS		AFM
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	responsivity	RBS
	photoconductivity	ion channeling

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gap		
impurity band		
transitions		

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gap	carrier concentration	
impurity band	mobilities	
transitions	junction properties	

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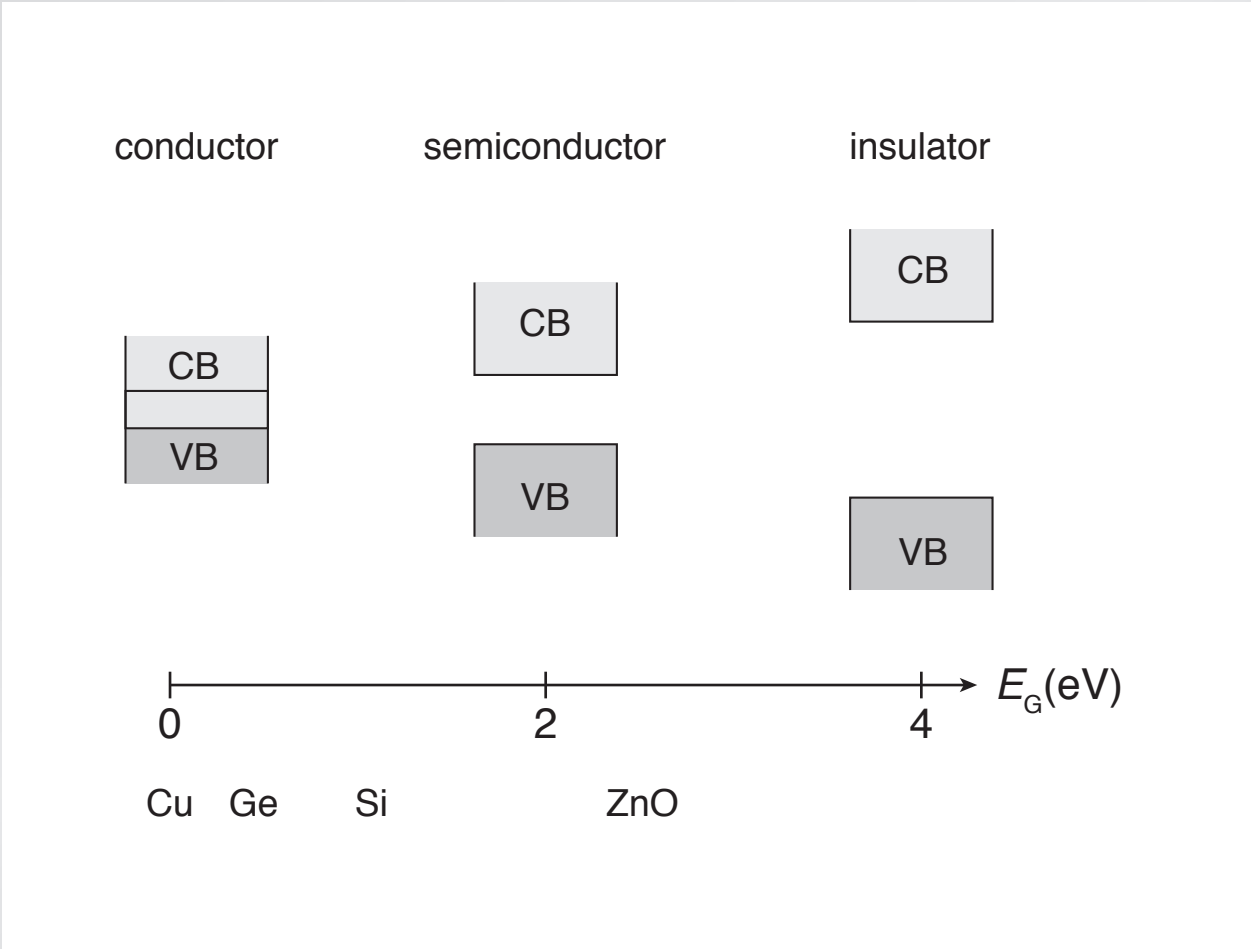
responsivity		RBS
photoconductivity		ion channeling
gap	carrier concentration	morphology
impurity band	mobilities	composition
transitions	junction properties	atomic structure

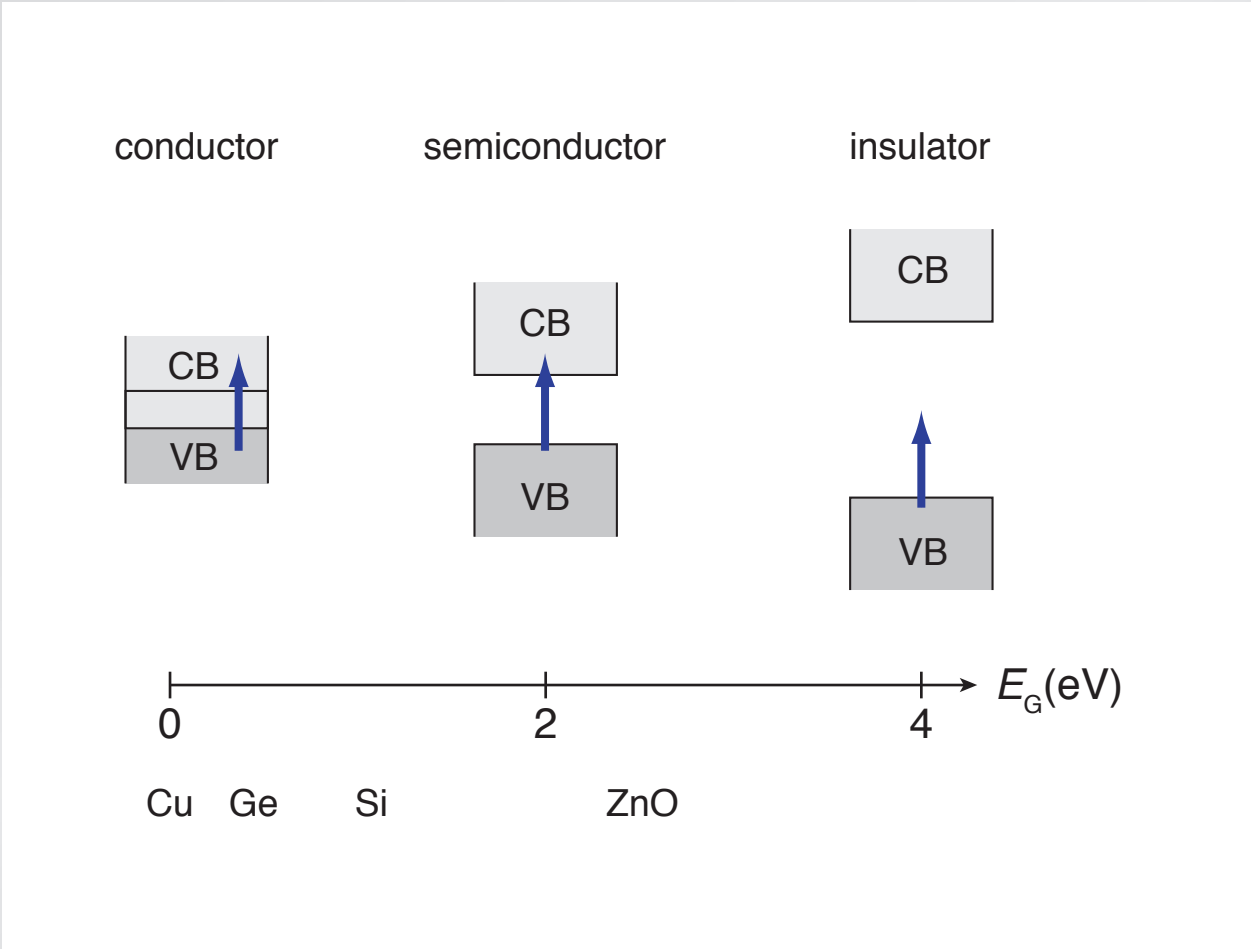
Introduction

new process & new class of material!



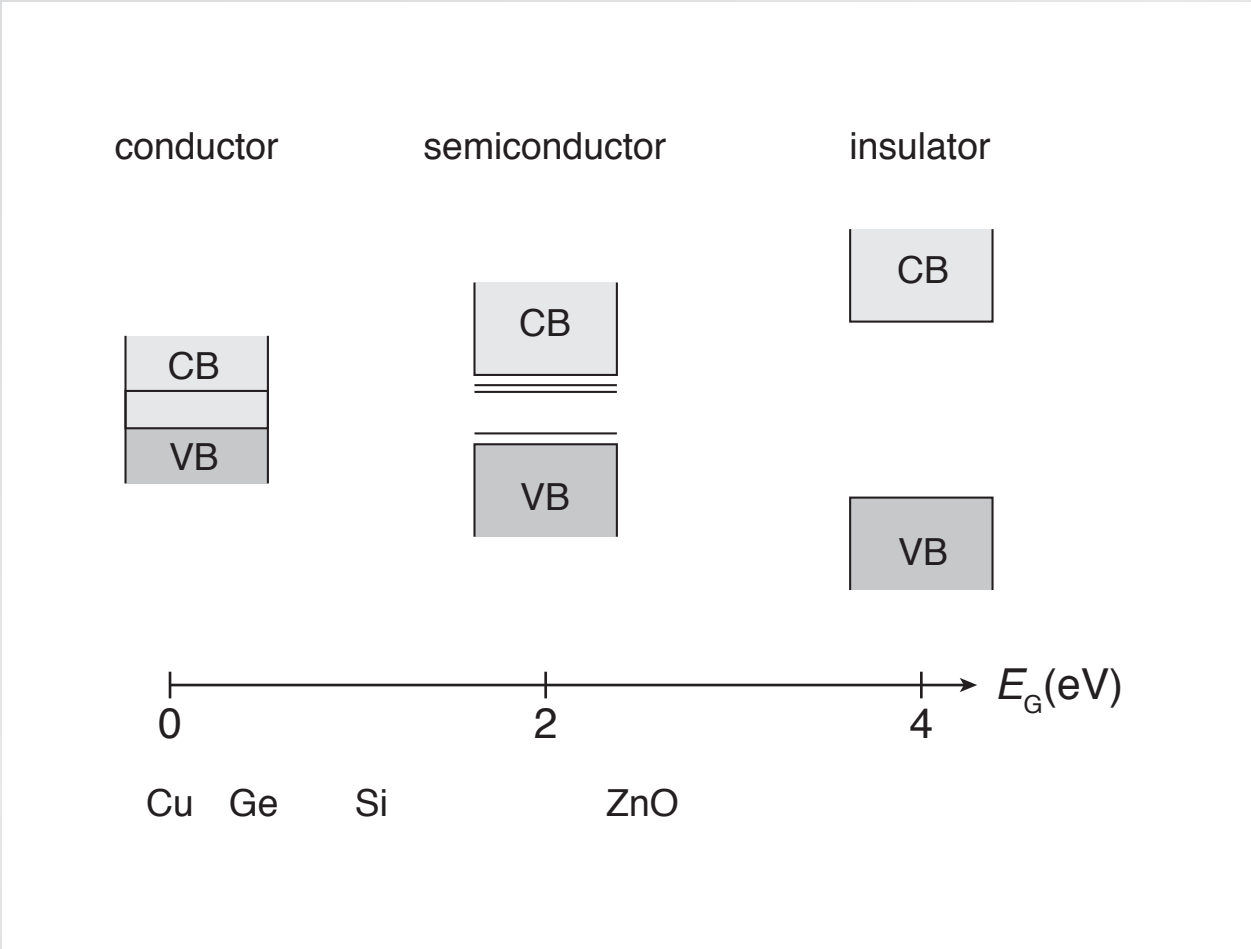
Introduction

gap determines optical and electronic properties



Introduction

shallow-level dopants control electronic properties



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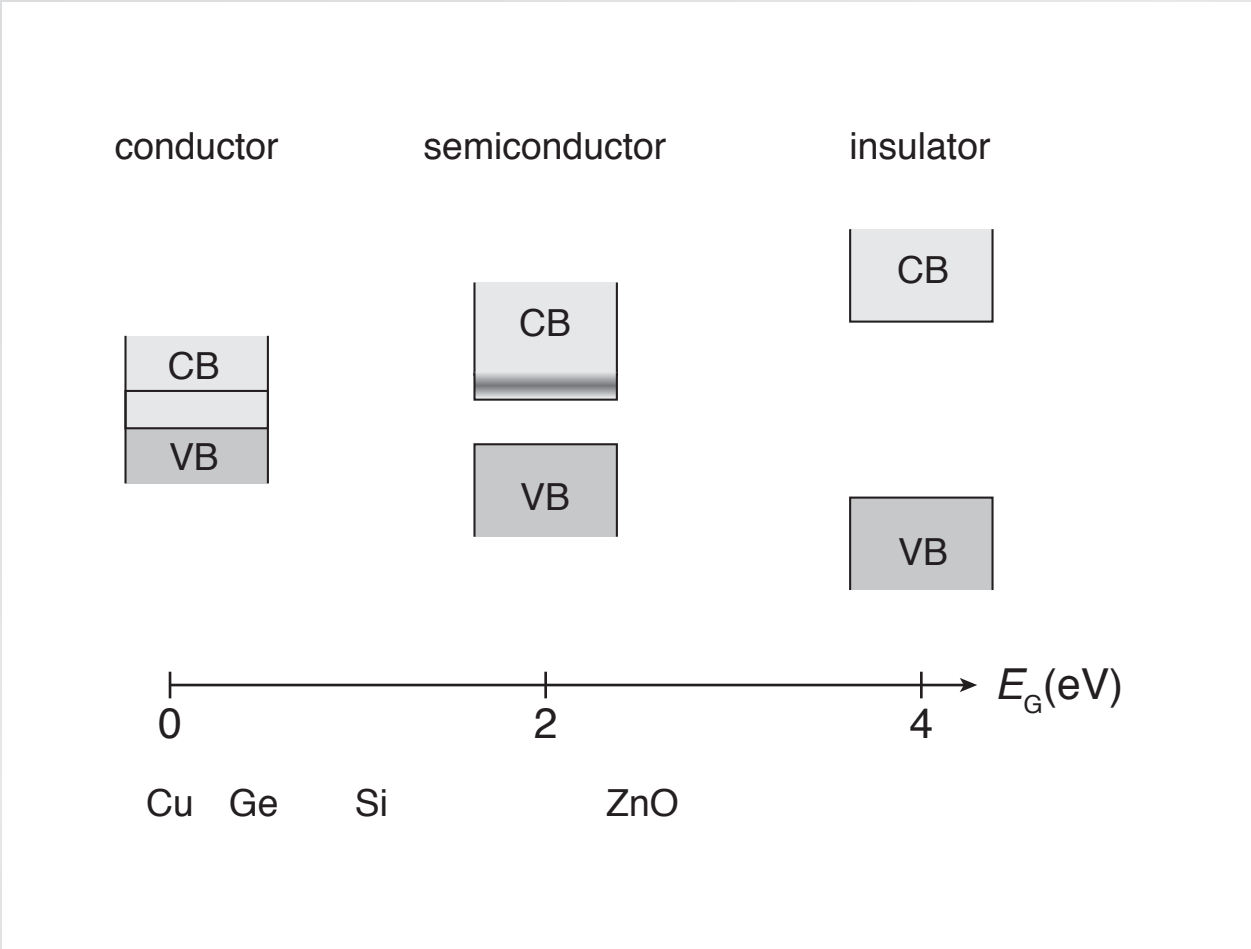
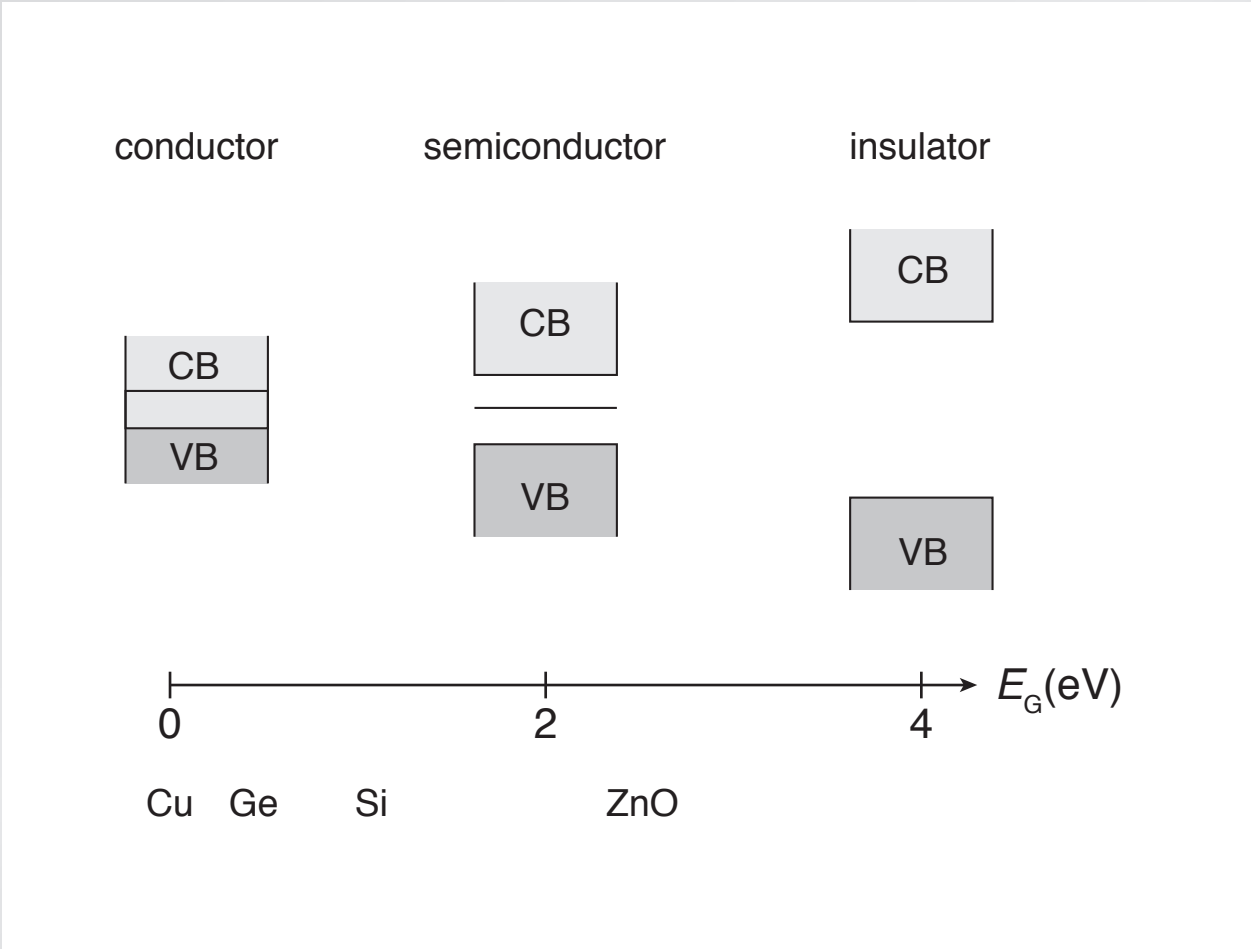


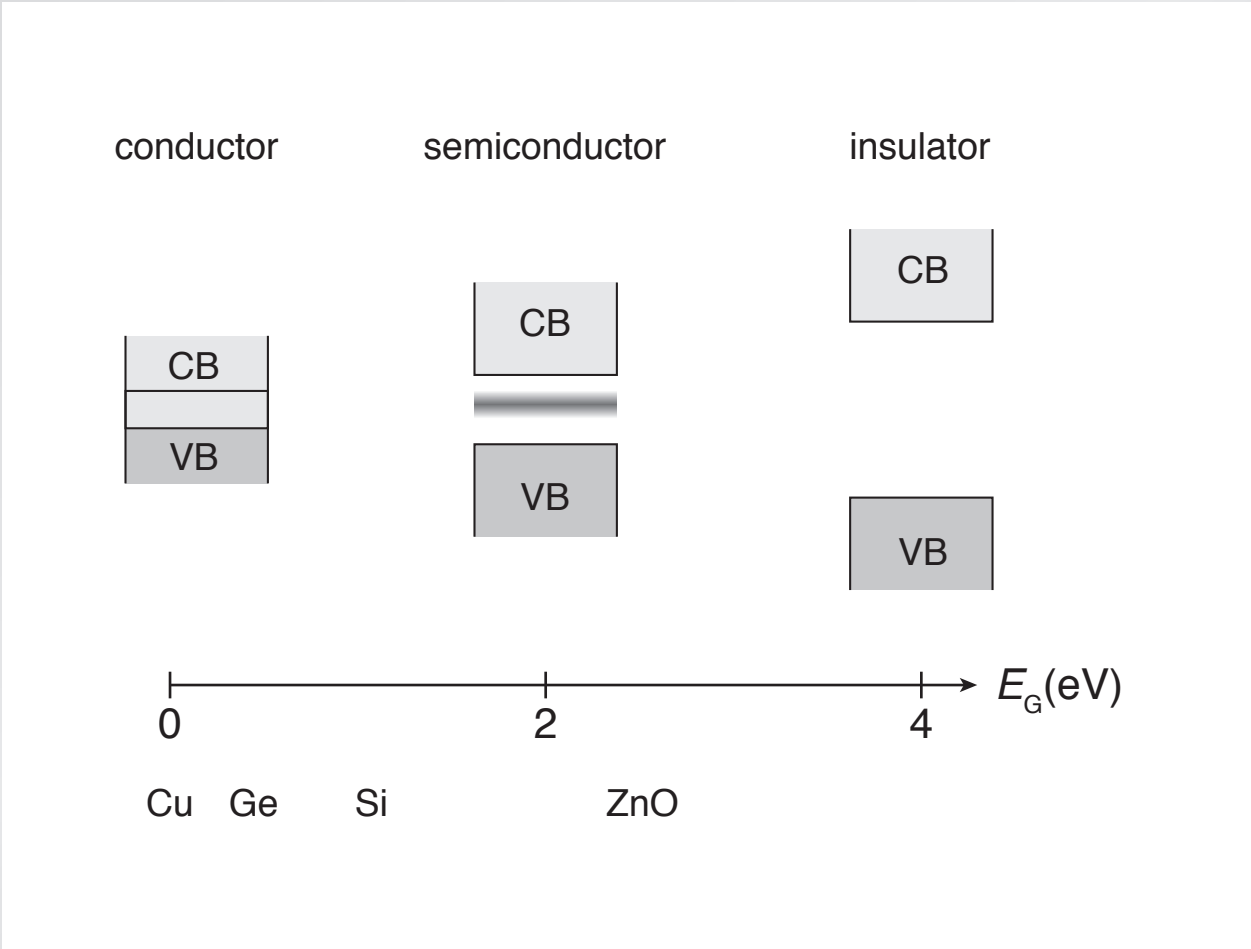
Introduction

deep-level dopants typically avoided



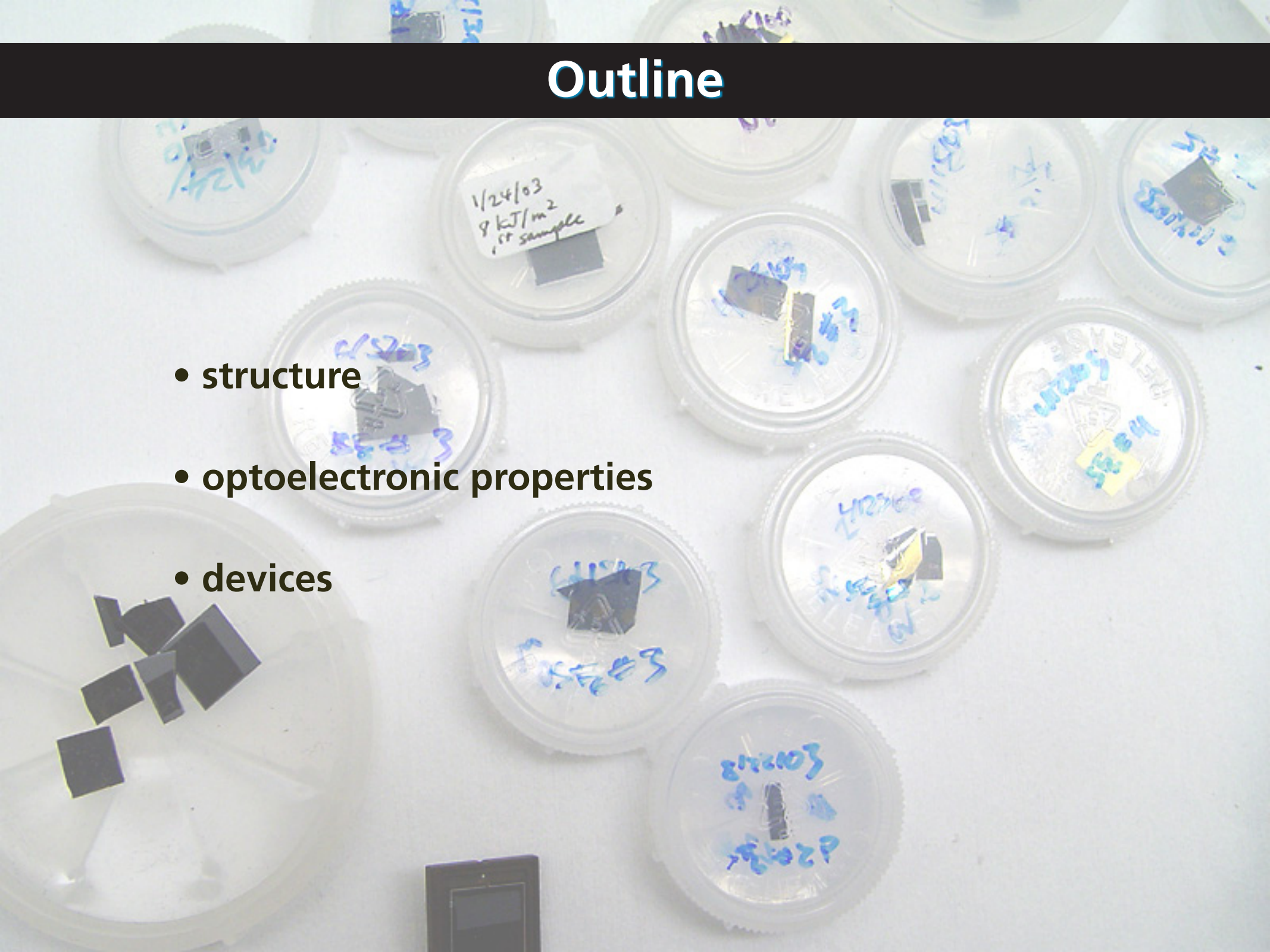
Introduction

femtosecond laser-doping gives rise to intermediate band

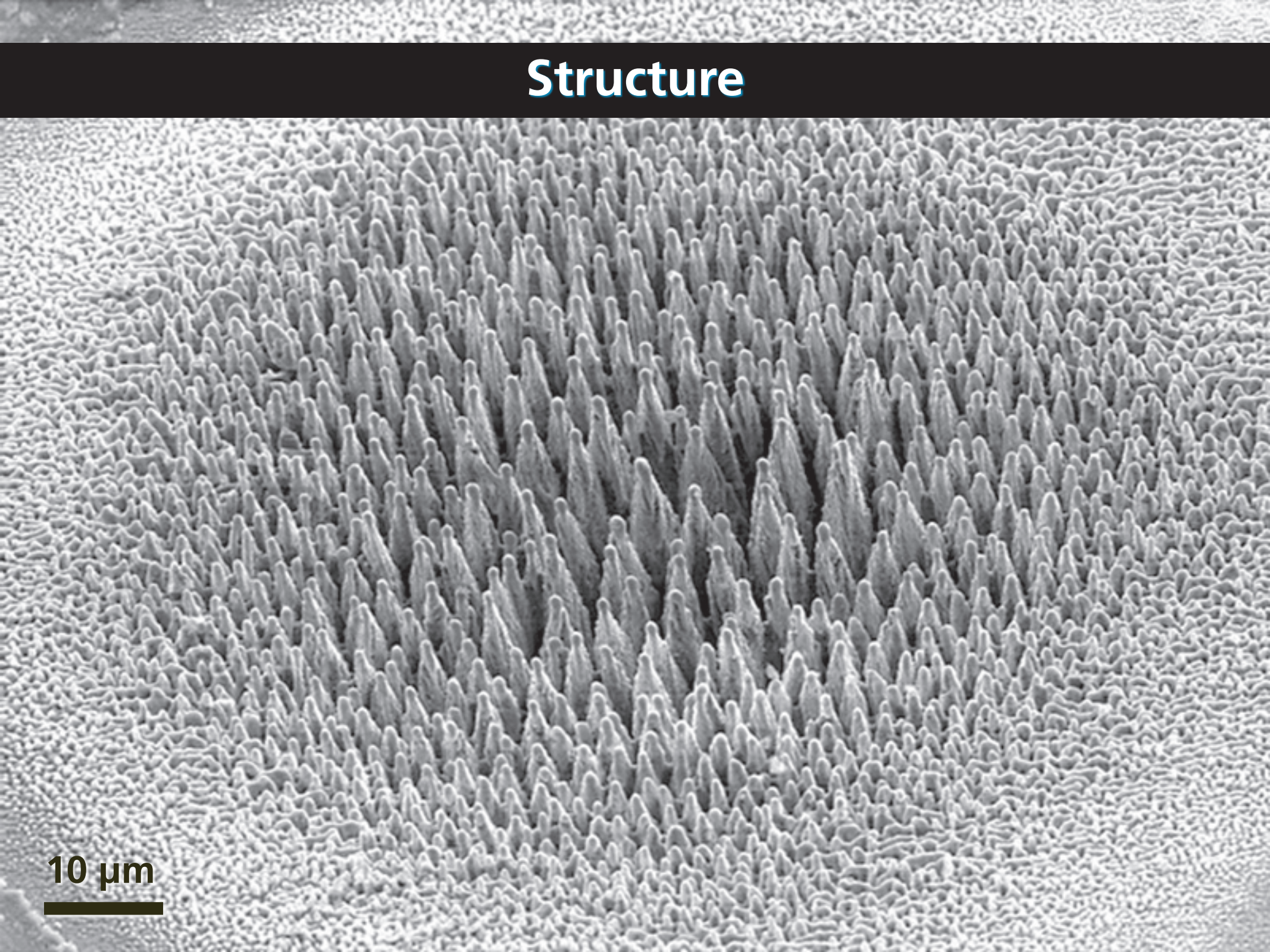


Outline

- structure
- optoelectronic properties
- devices



Structure



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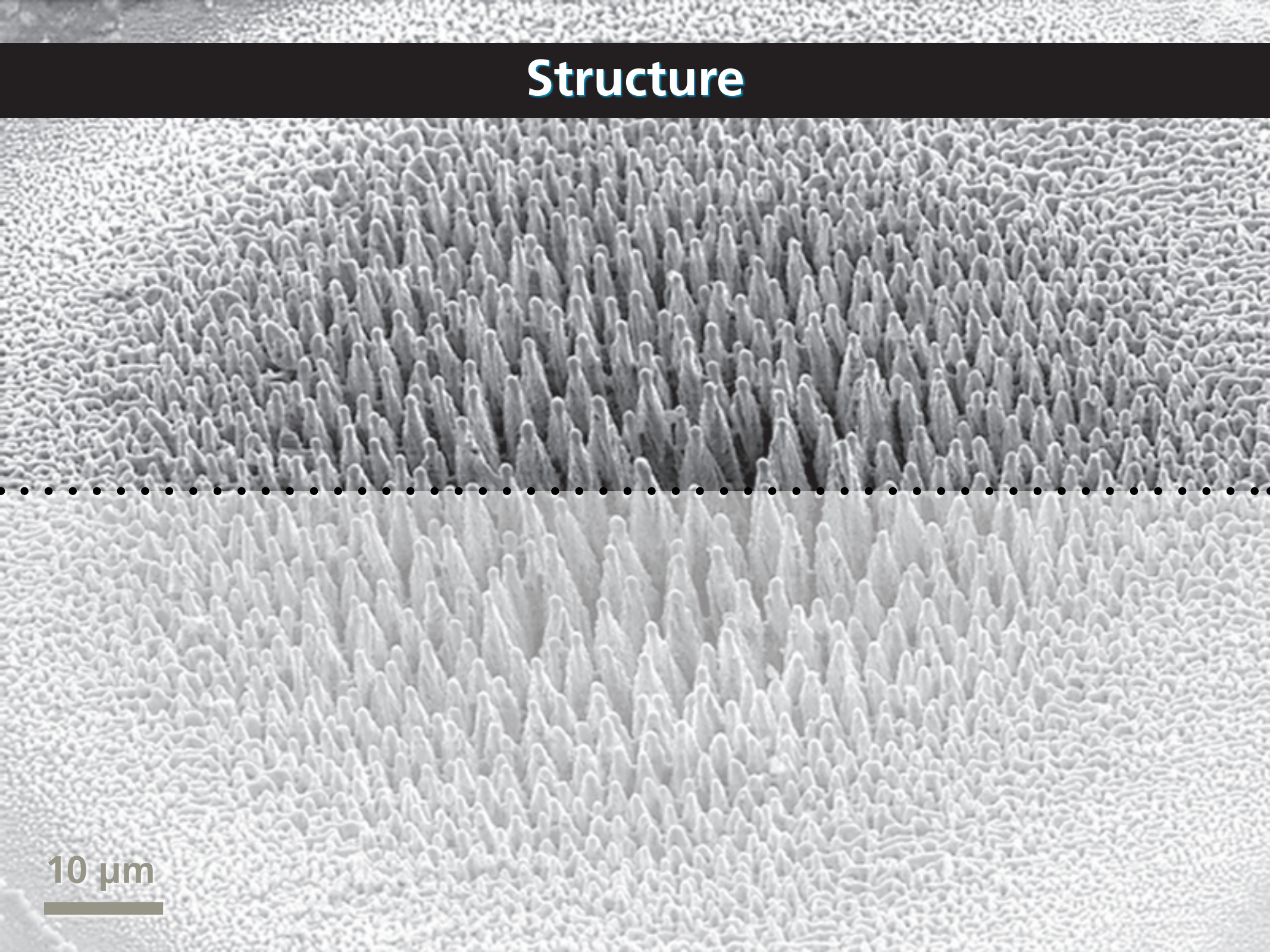

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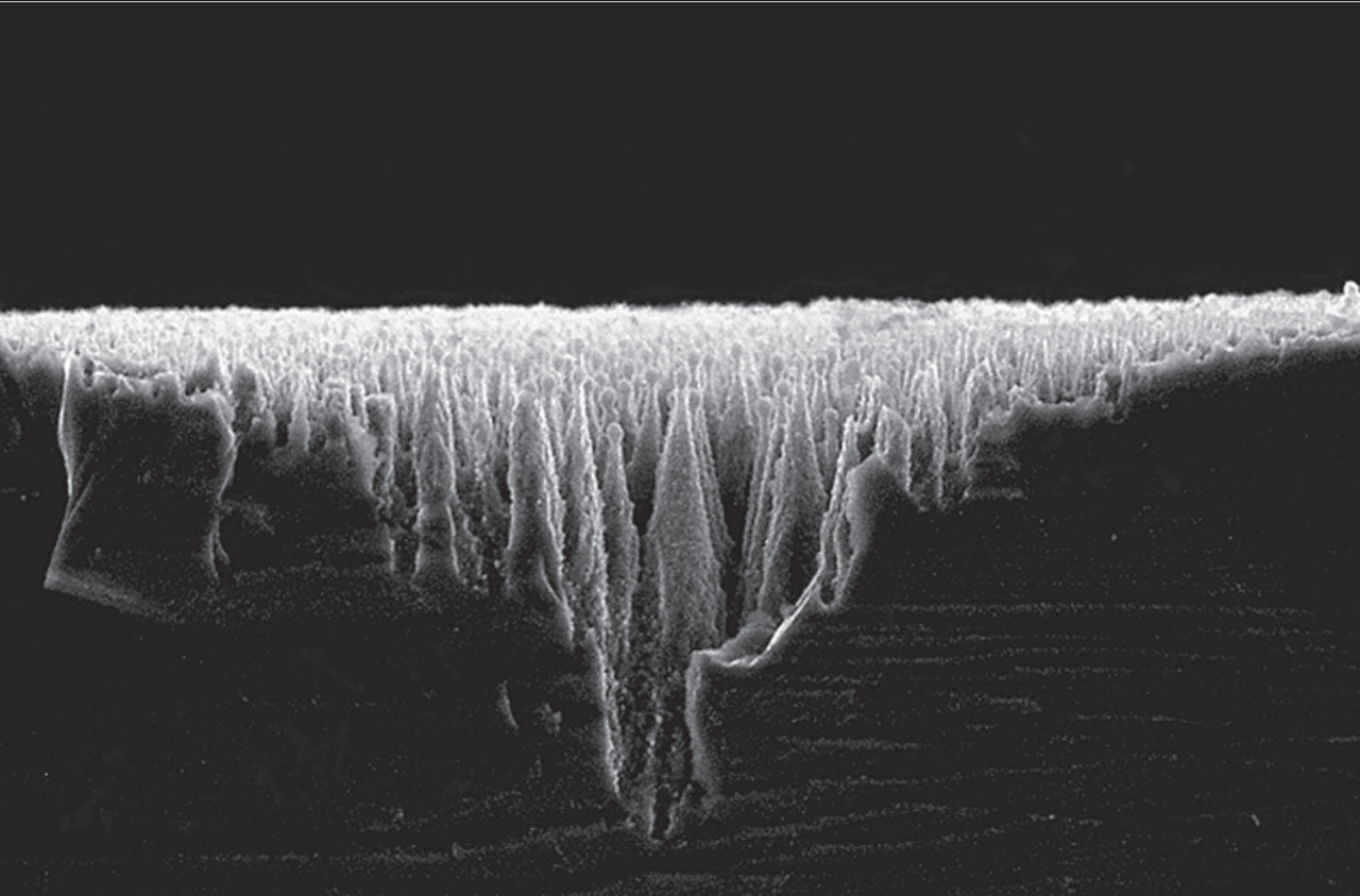

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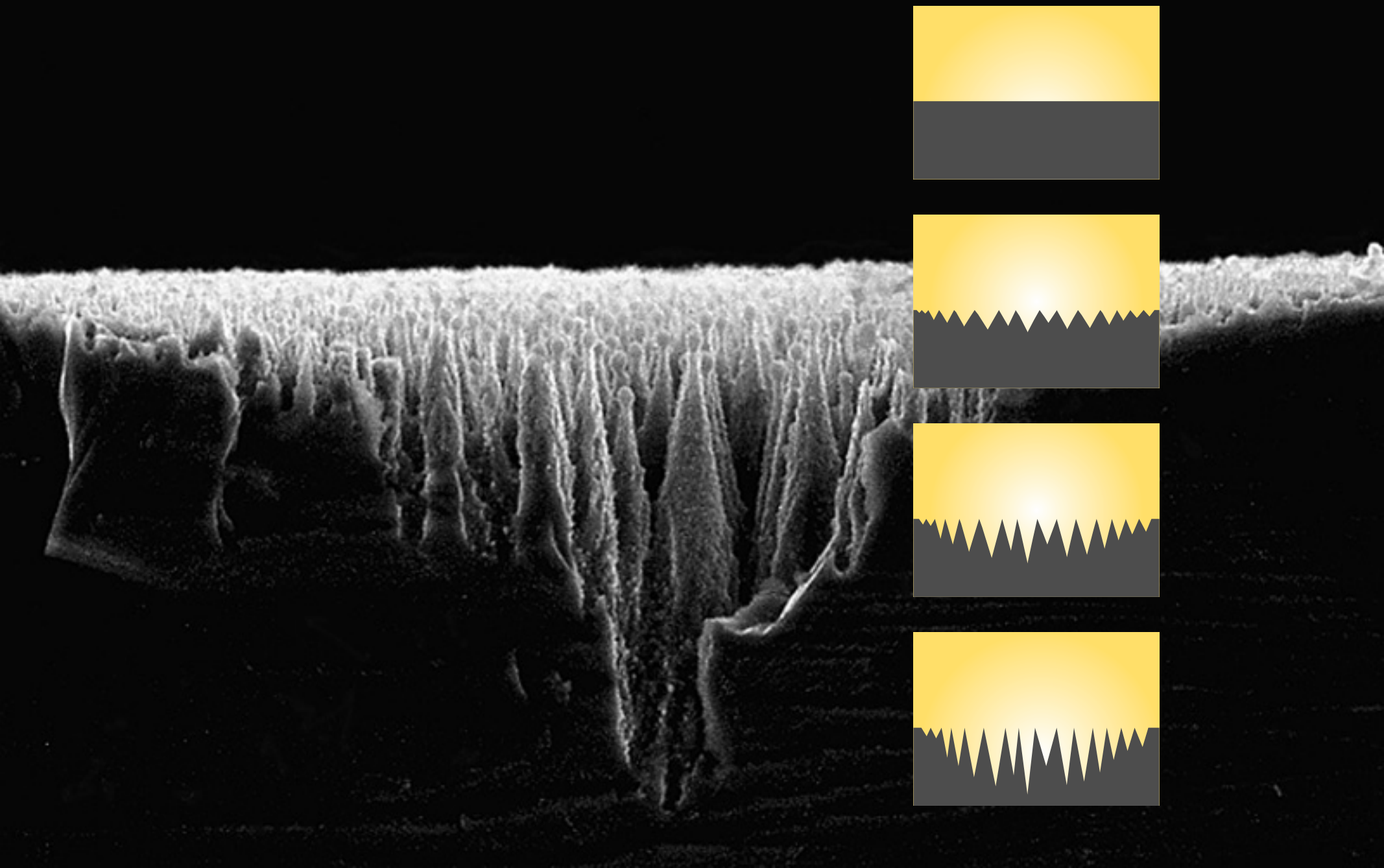

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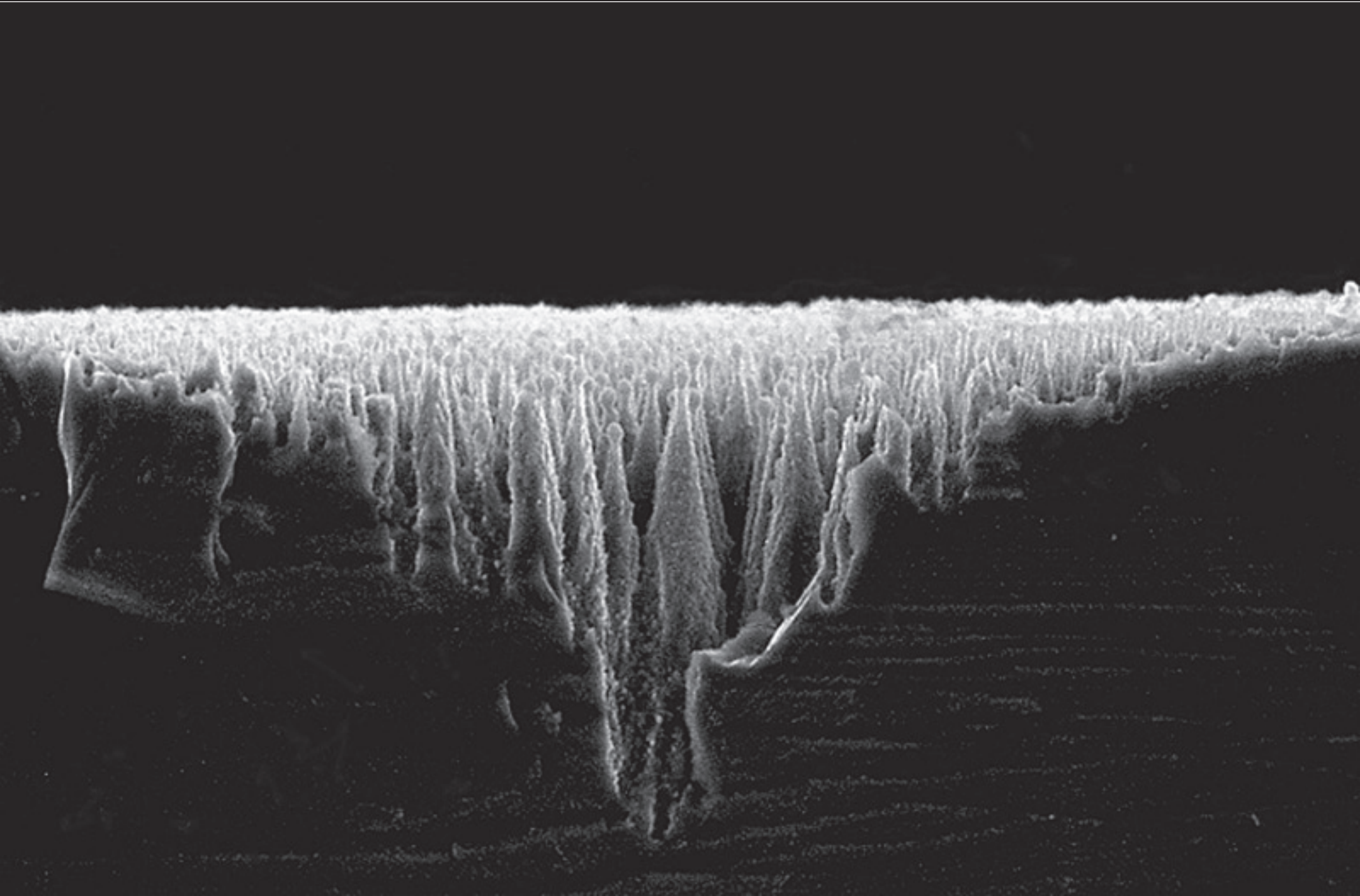

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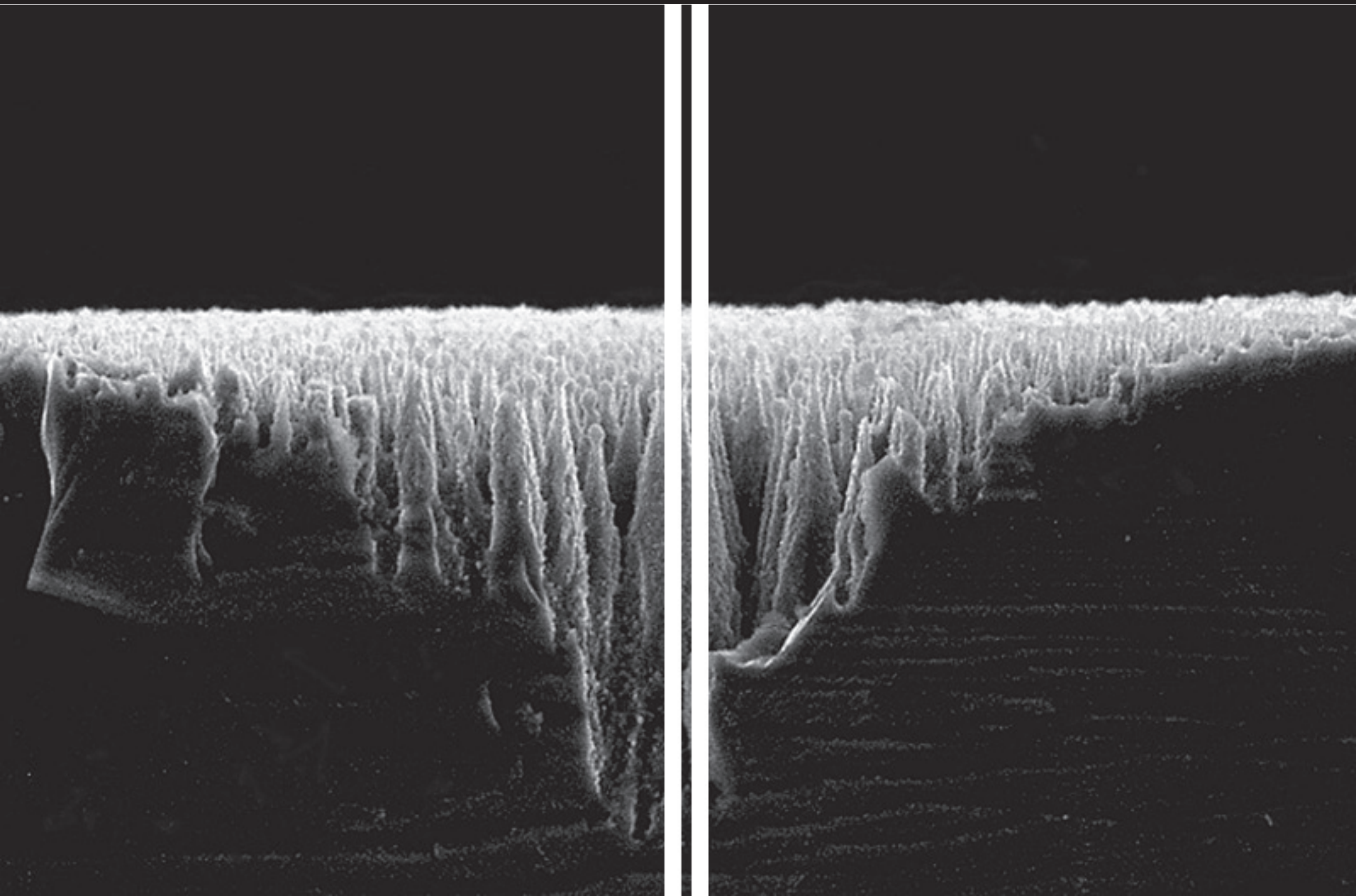
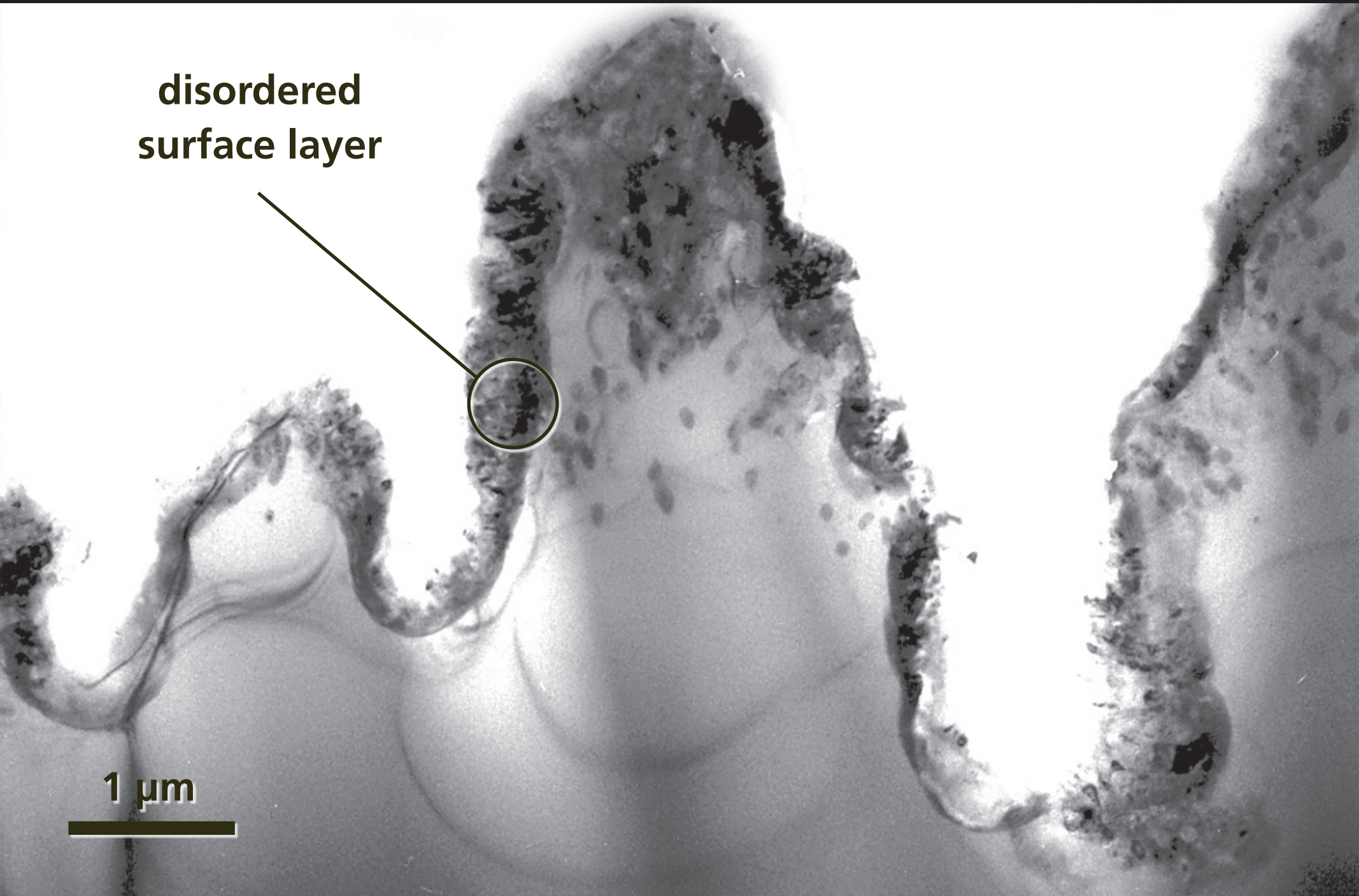


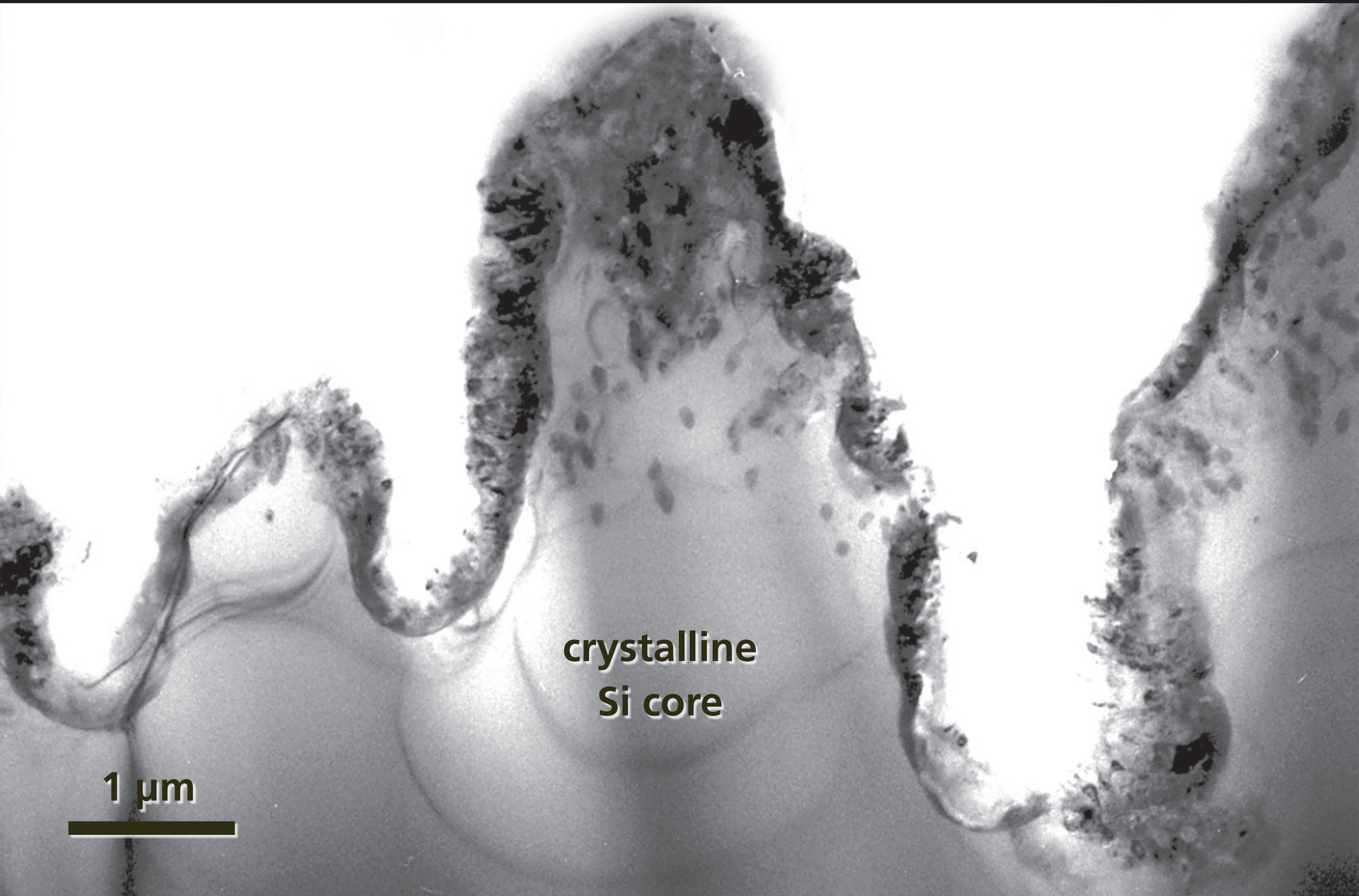
Structure

cross-sectional
Transmission Electron
Microscopy

Structure



Structure



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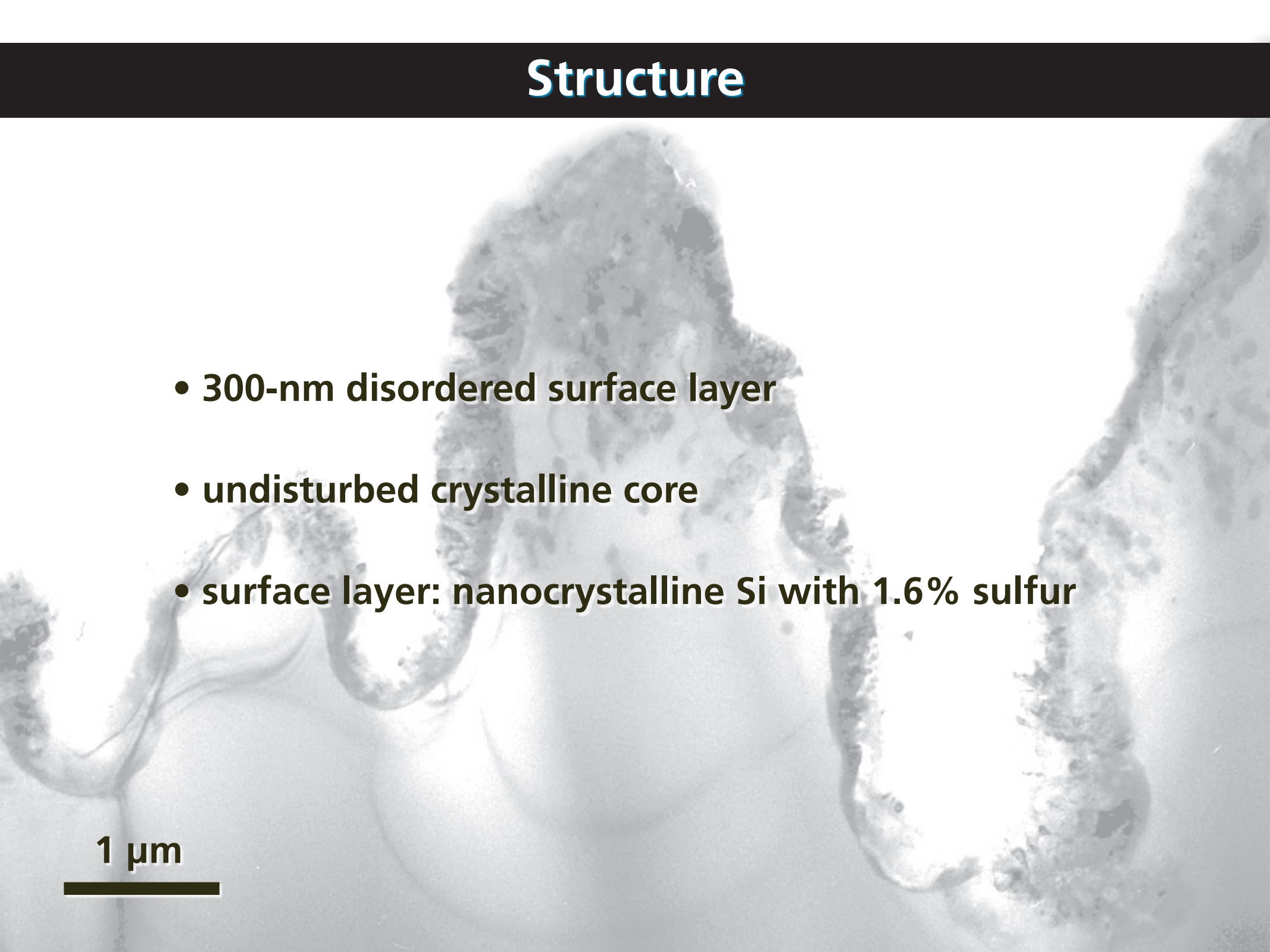


- 300-nm disordered surface layer
- undisturbed crystalline core
- surface layer: nanocrystalline Si with 1.6% sulfur

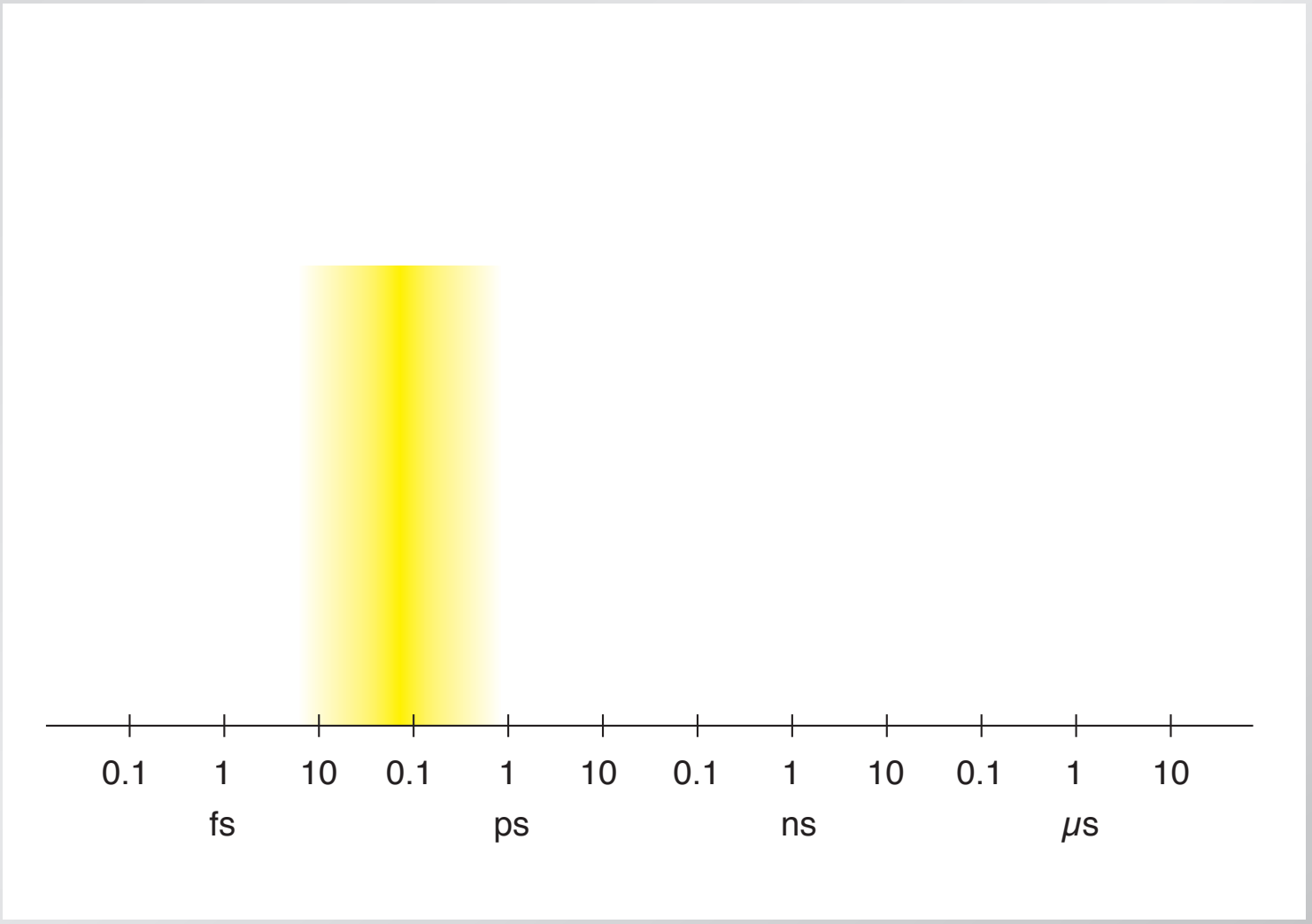
1 µm

Structure

two processes: melting and ablation

Structure

relevant time scales



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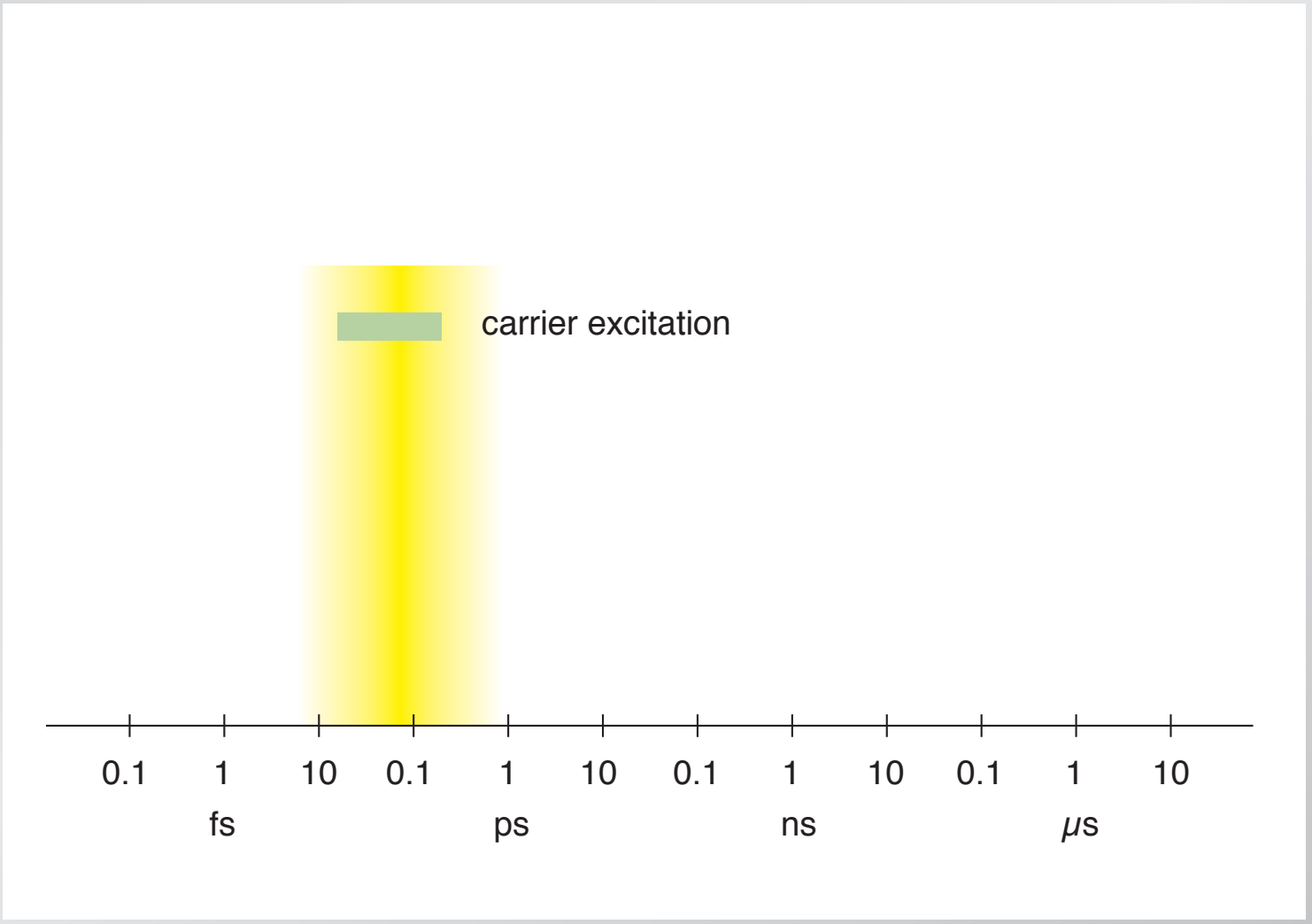

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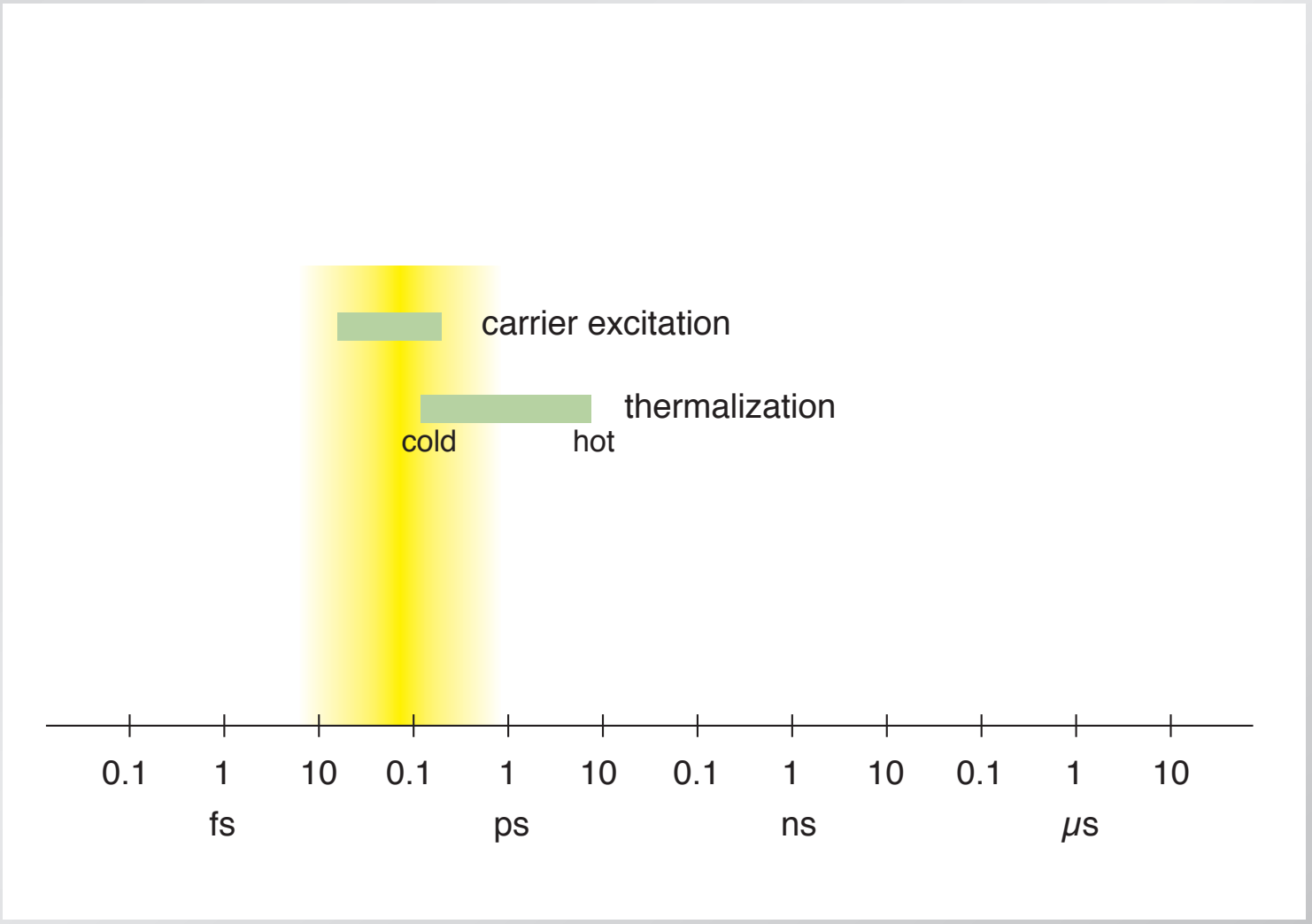
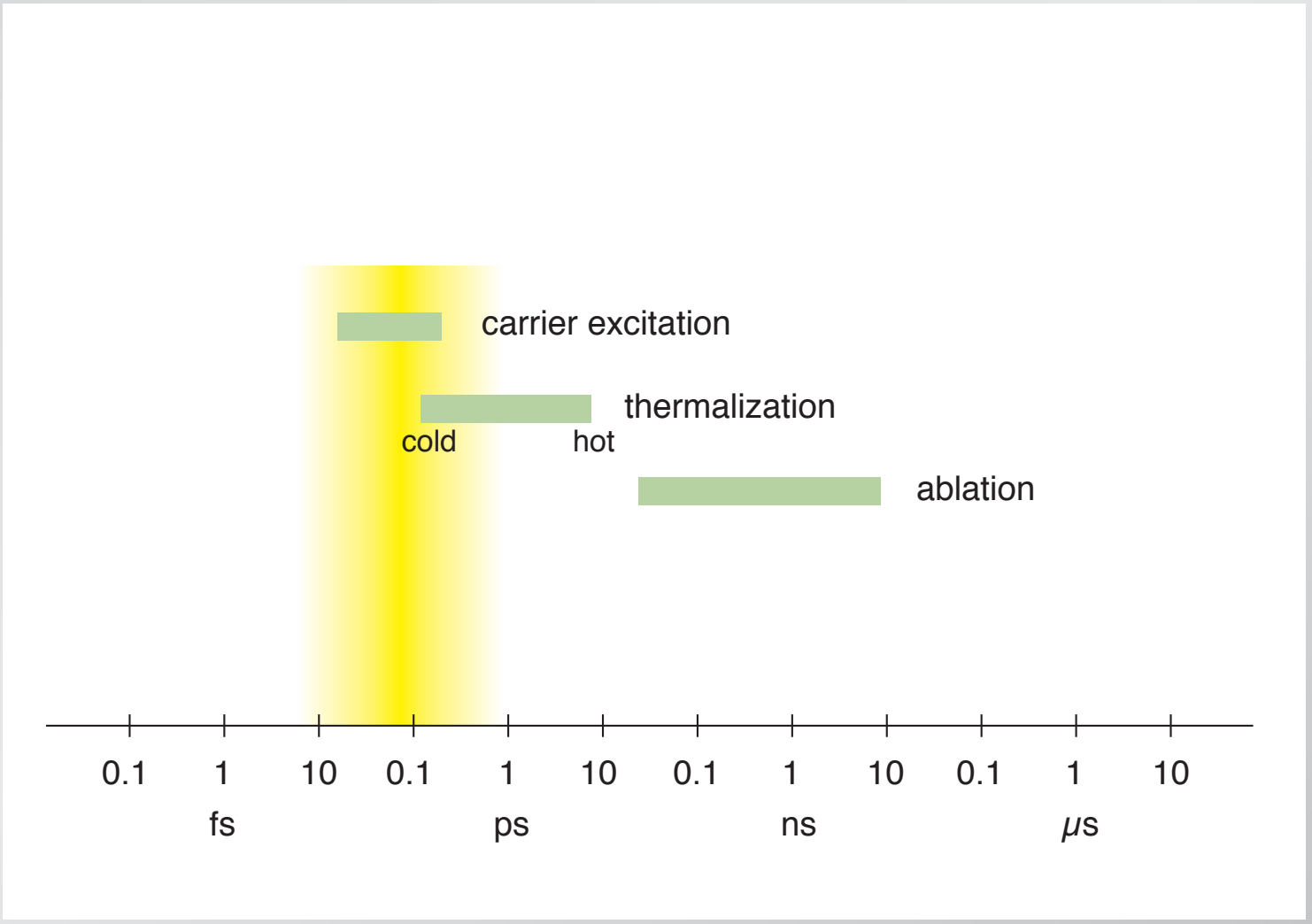
relevant time scales



Structure

relevant time scales



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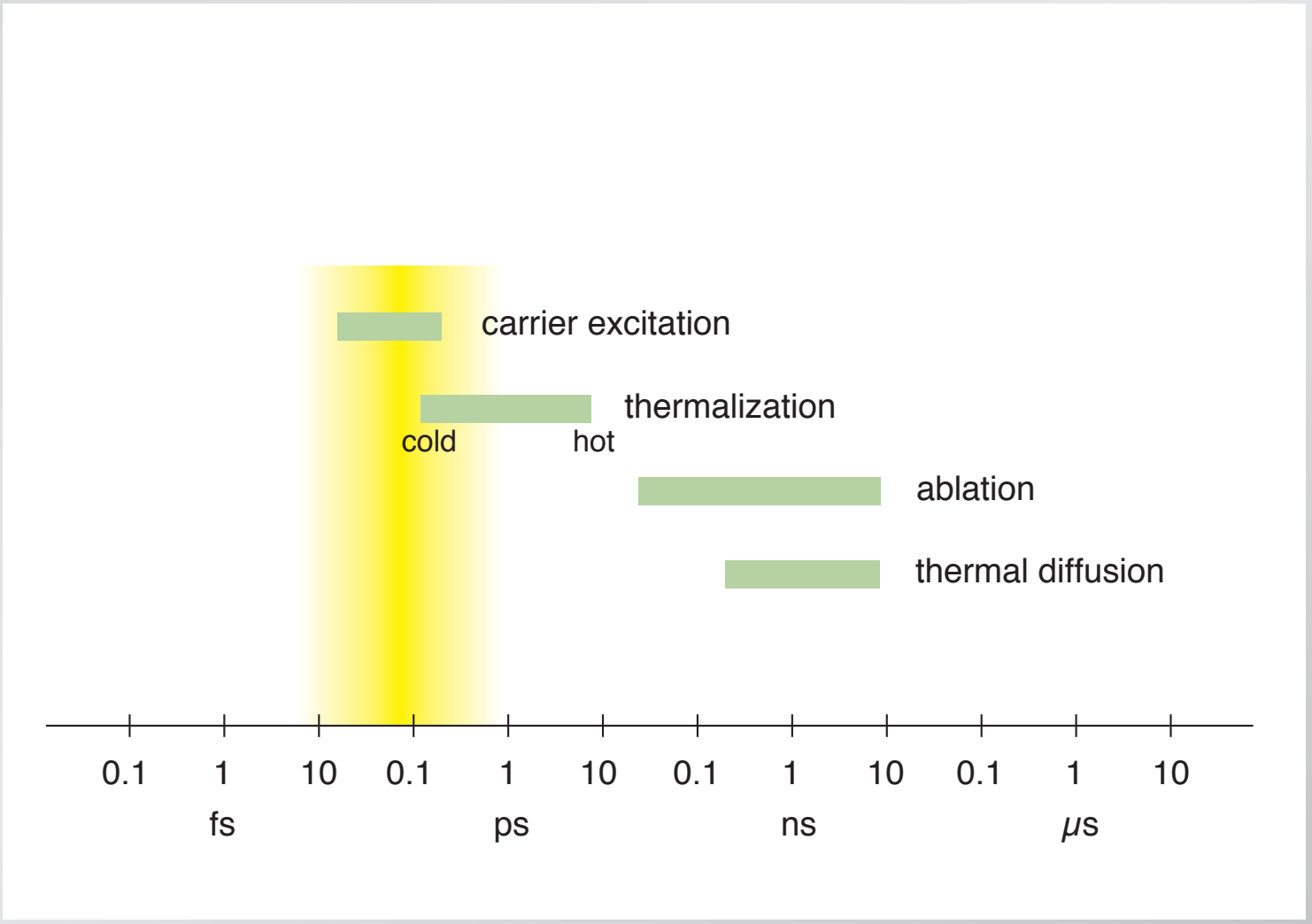

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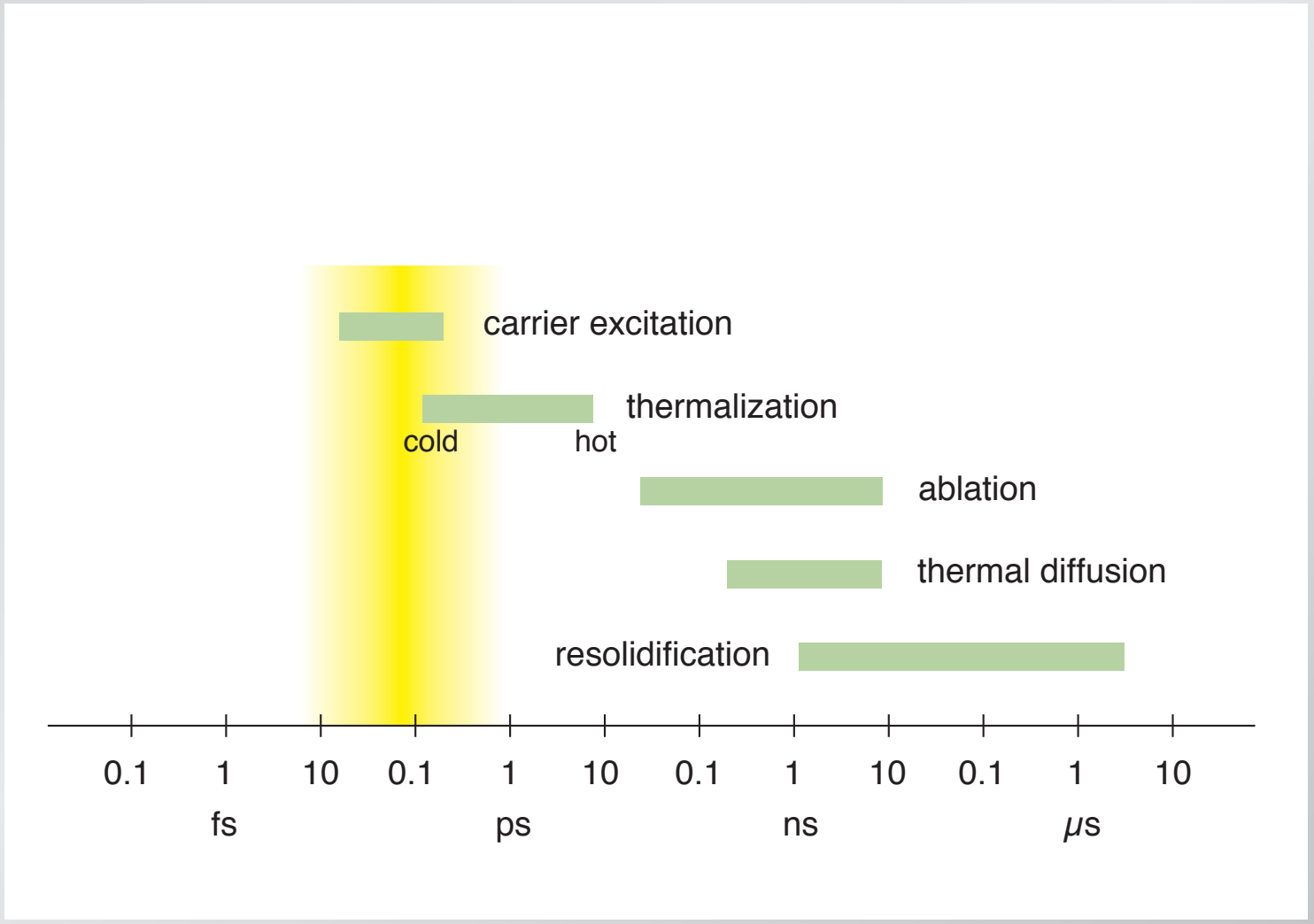

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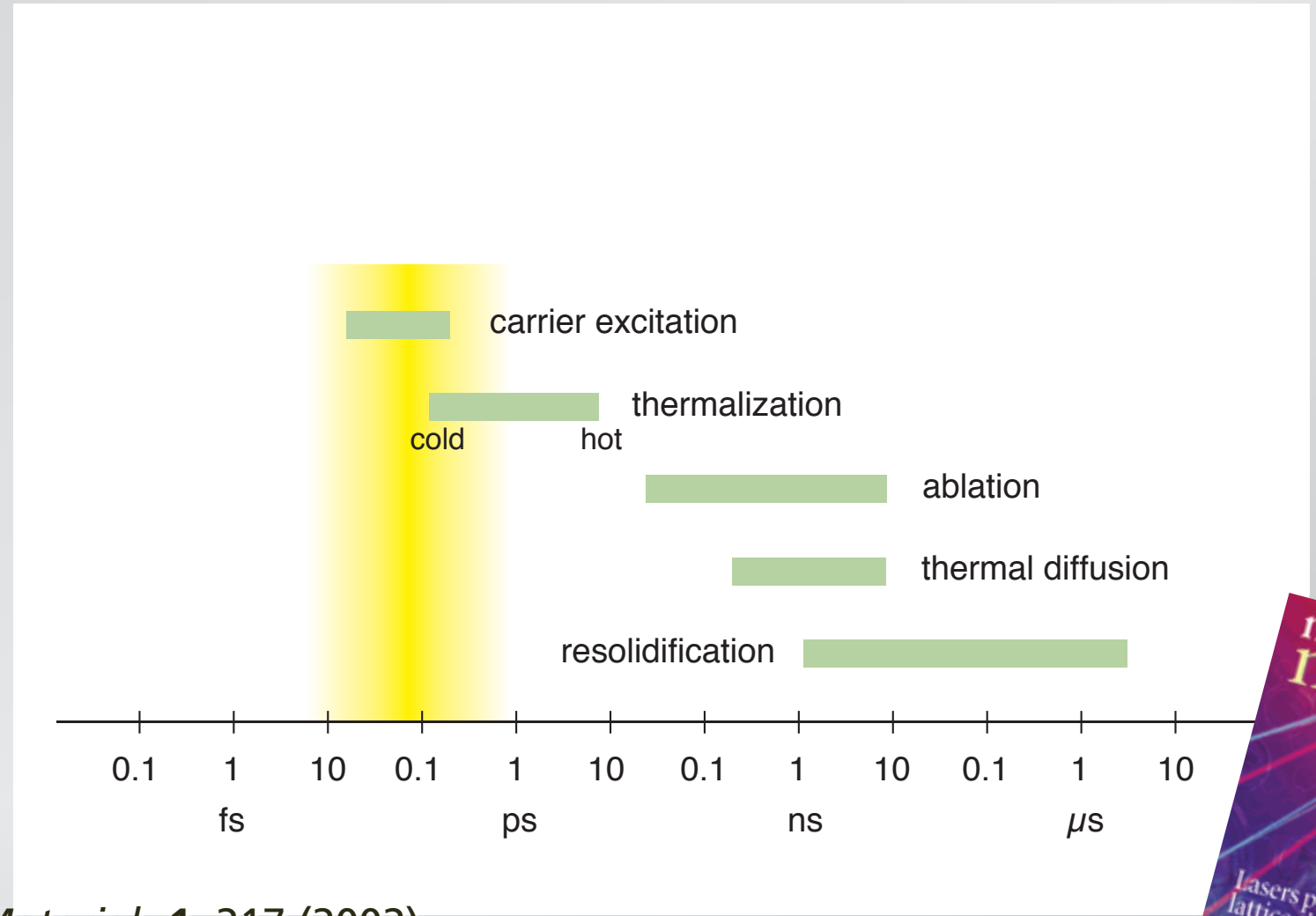
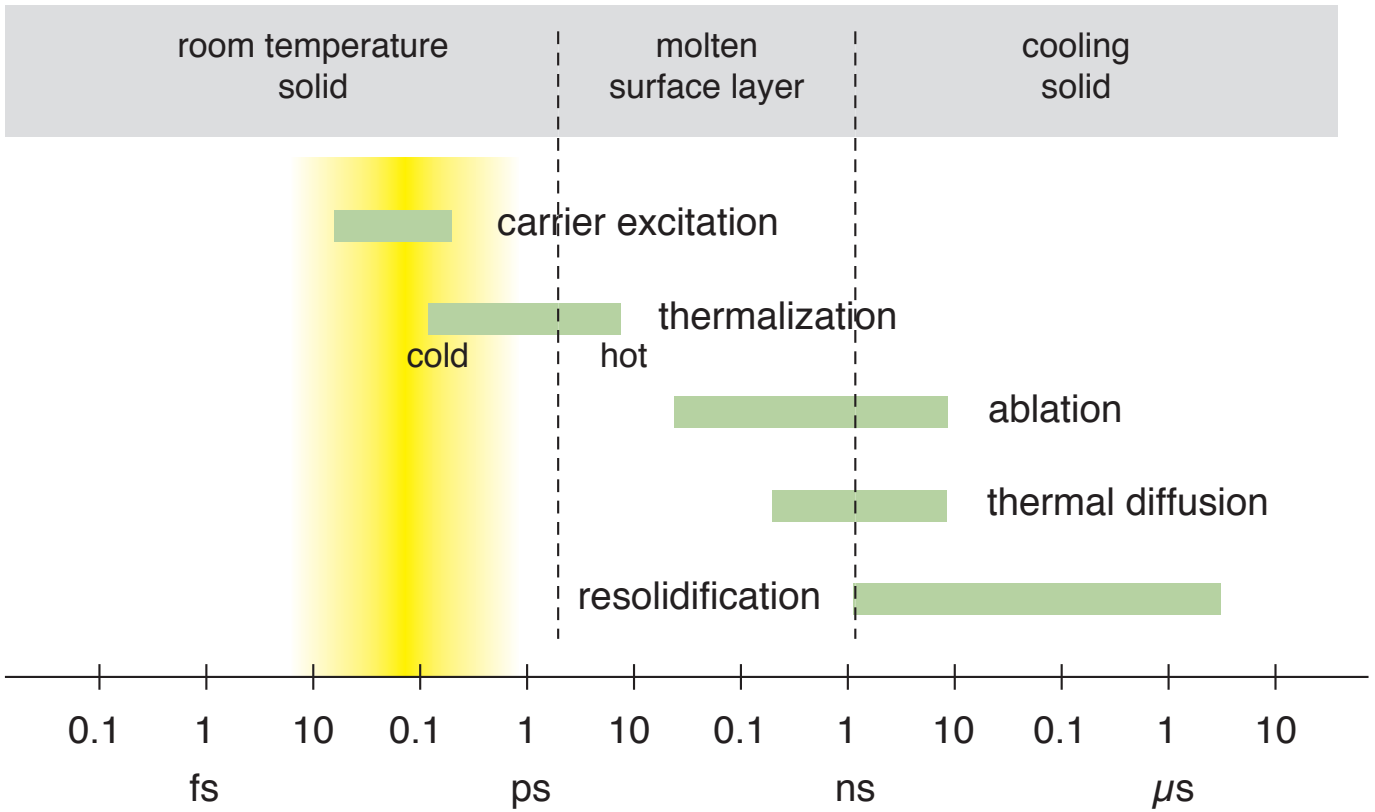


Nature Materials **1**, 217 (2002)

Structure

relevant time scales



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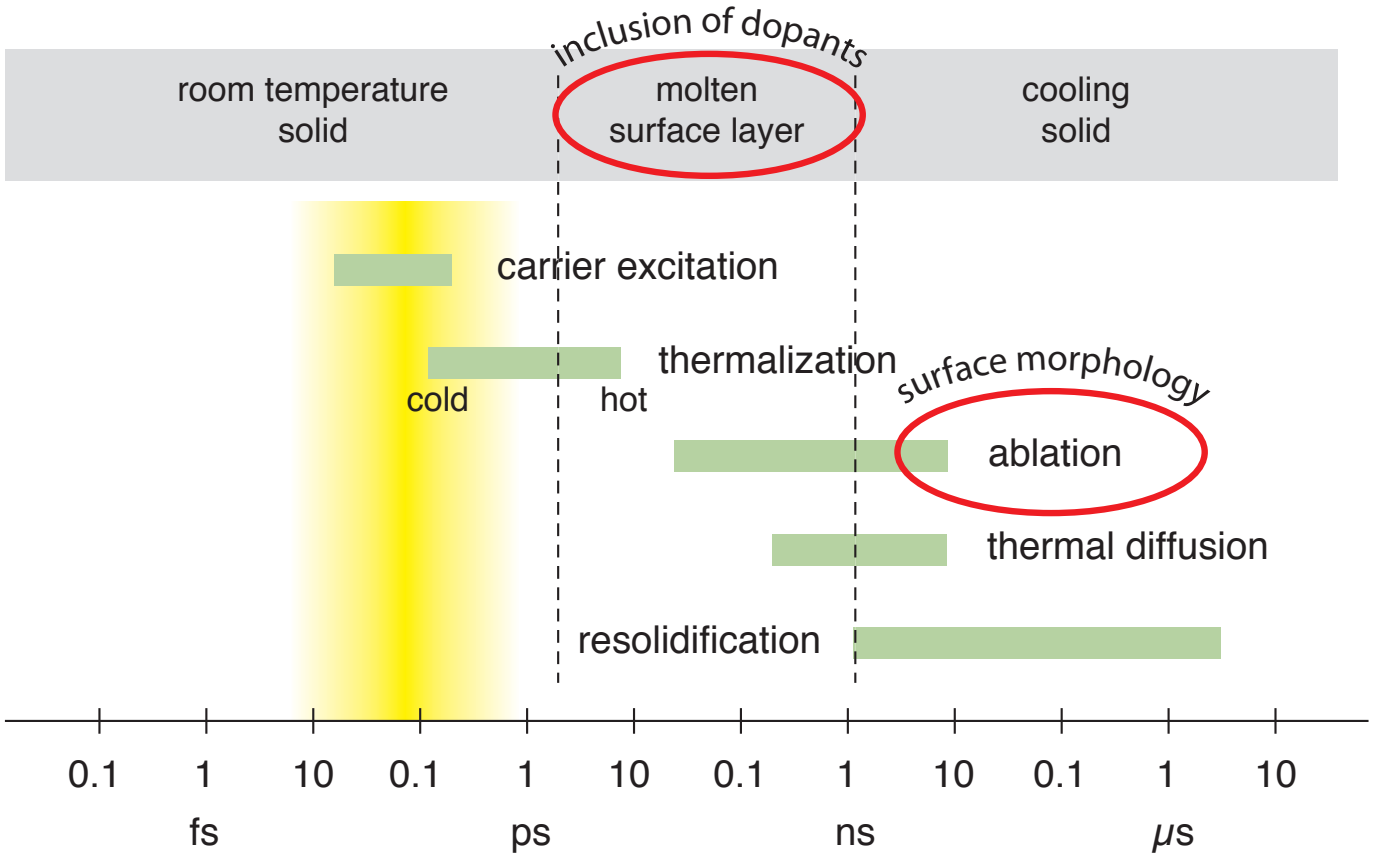


Structure

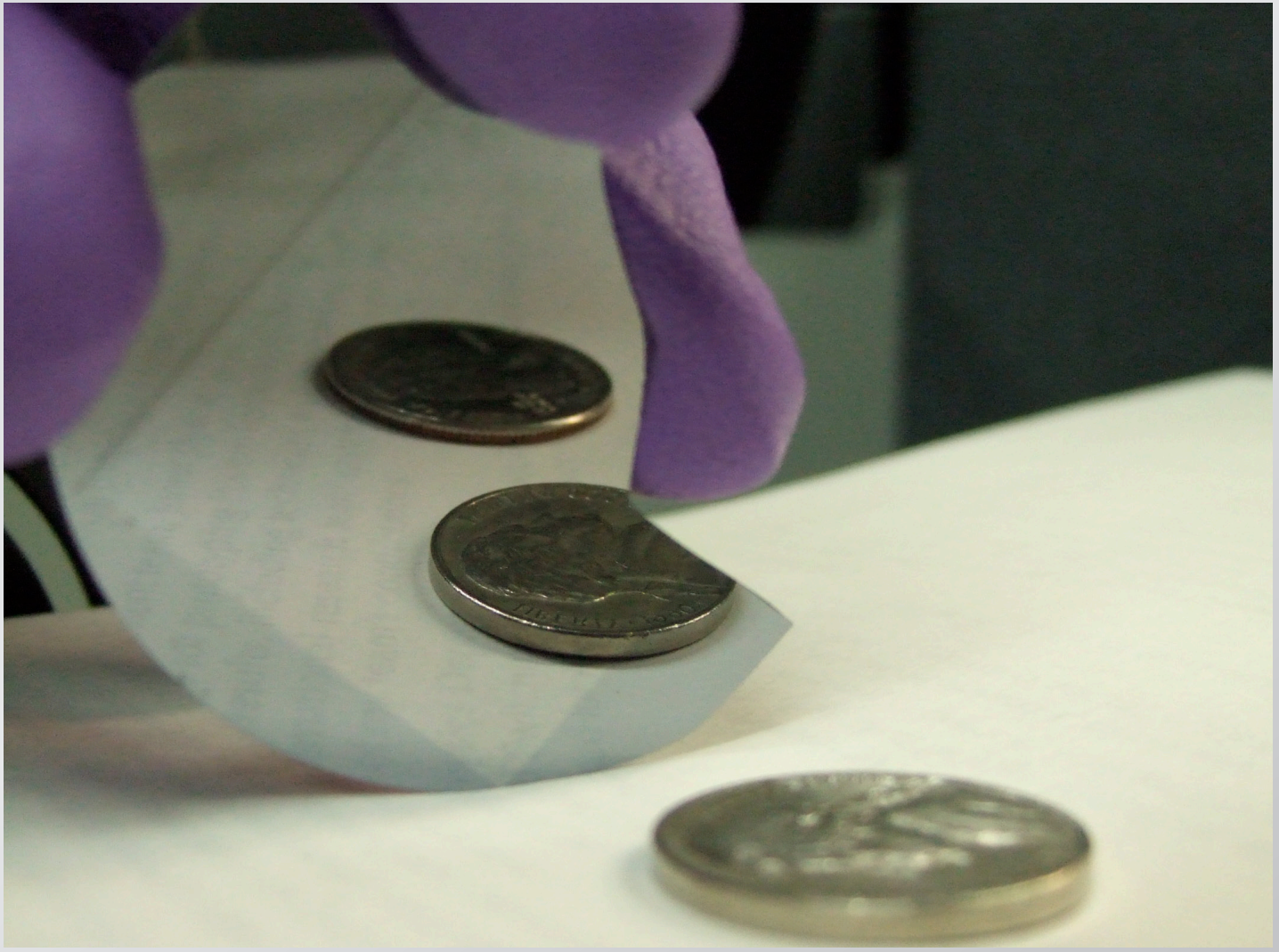
different thresholds:

melting: 1.5 kJ/m^2

ablation: 3.1 kJ/m^2

Structure

decouple ablation from melting



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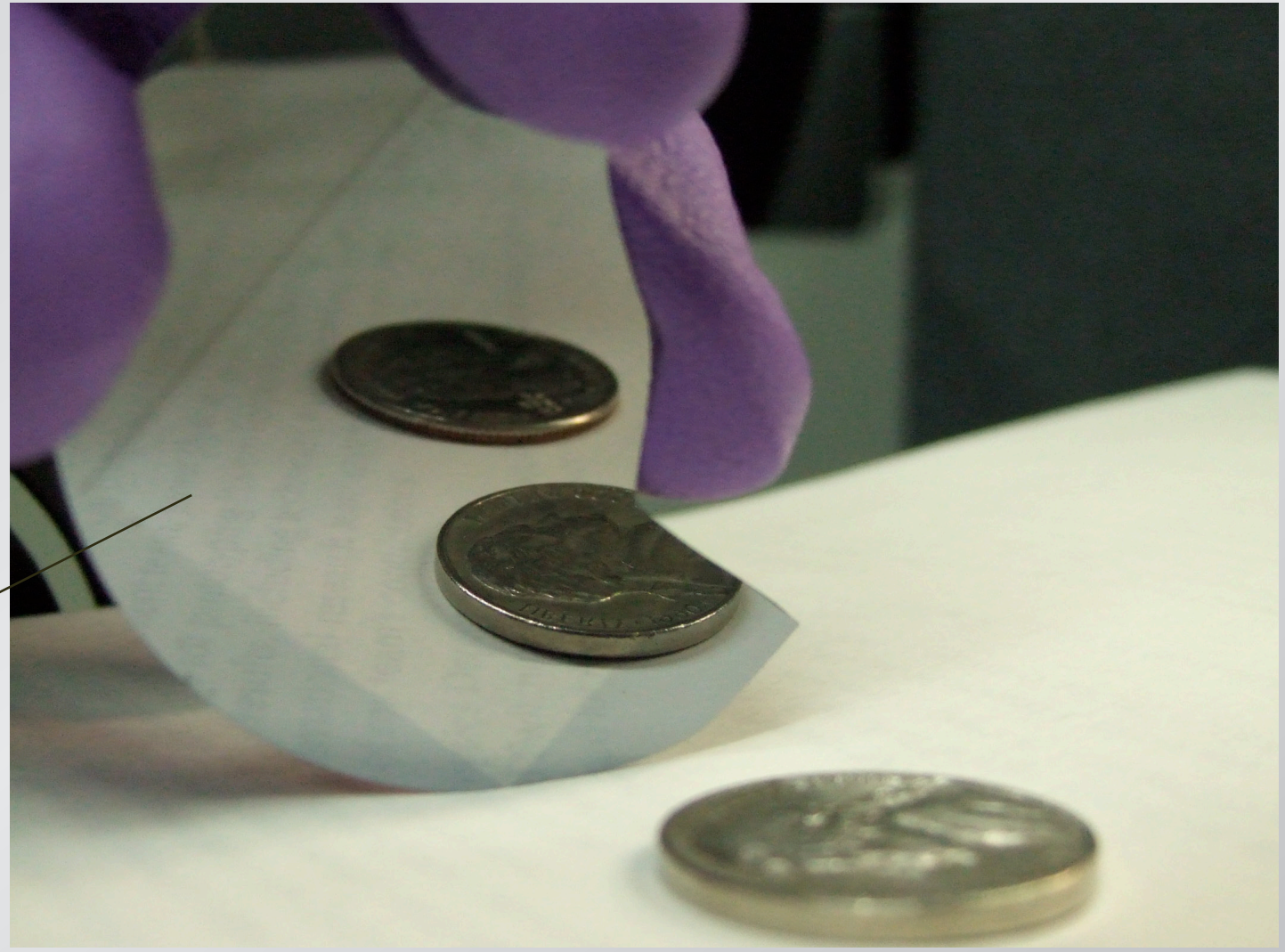

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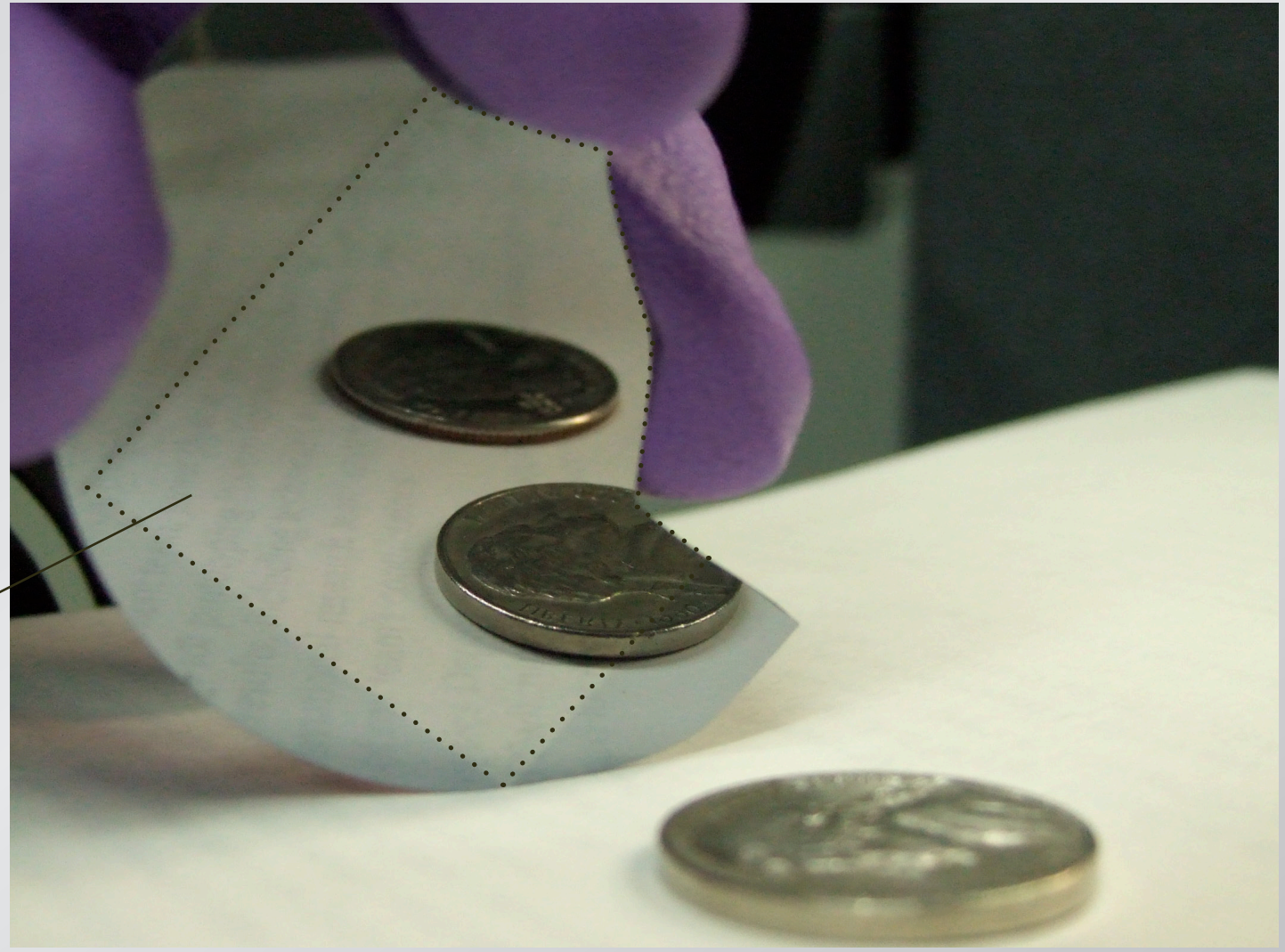

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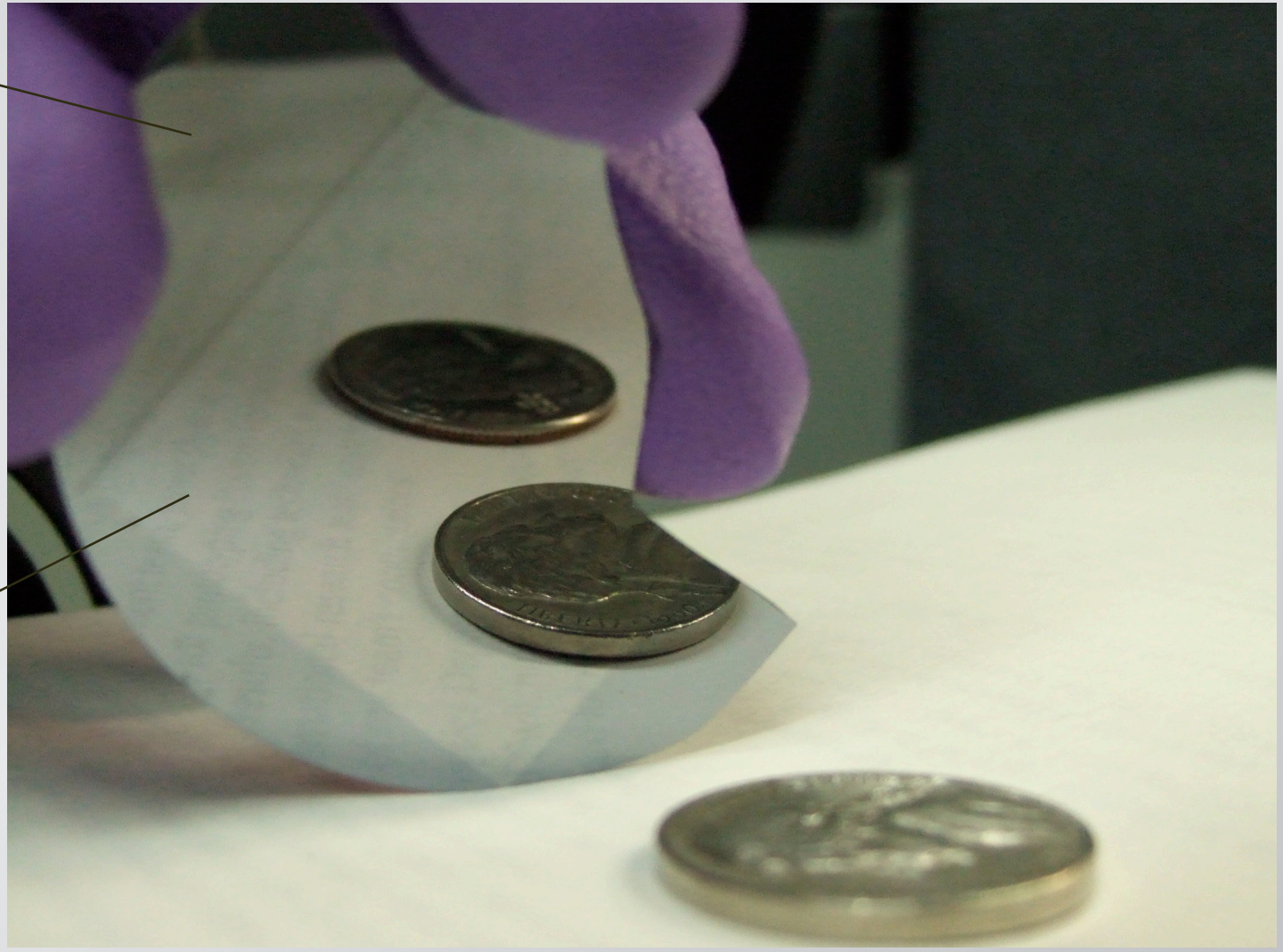

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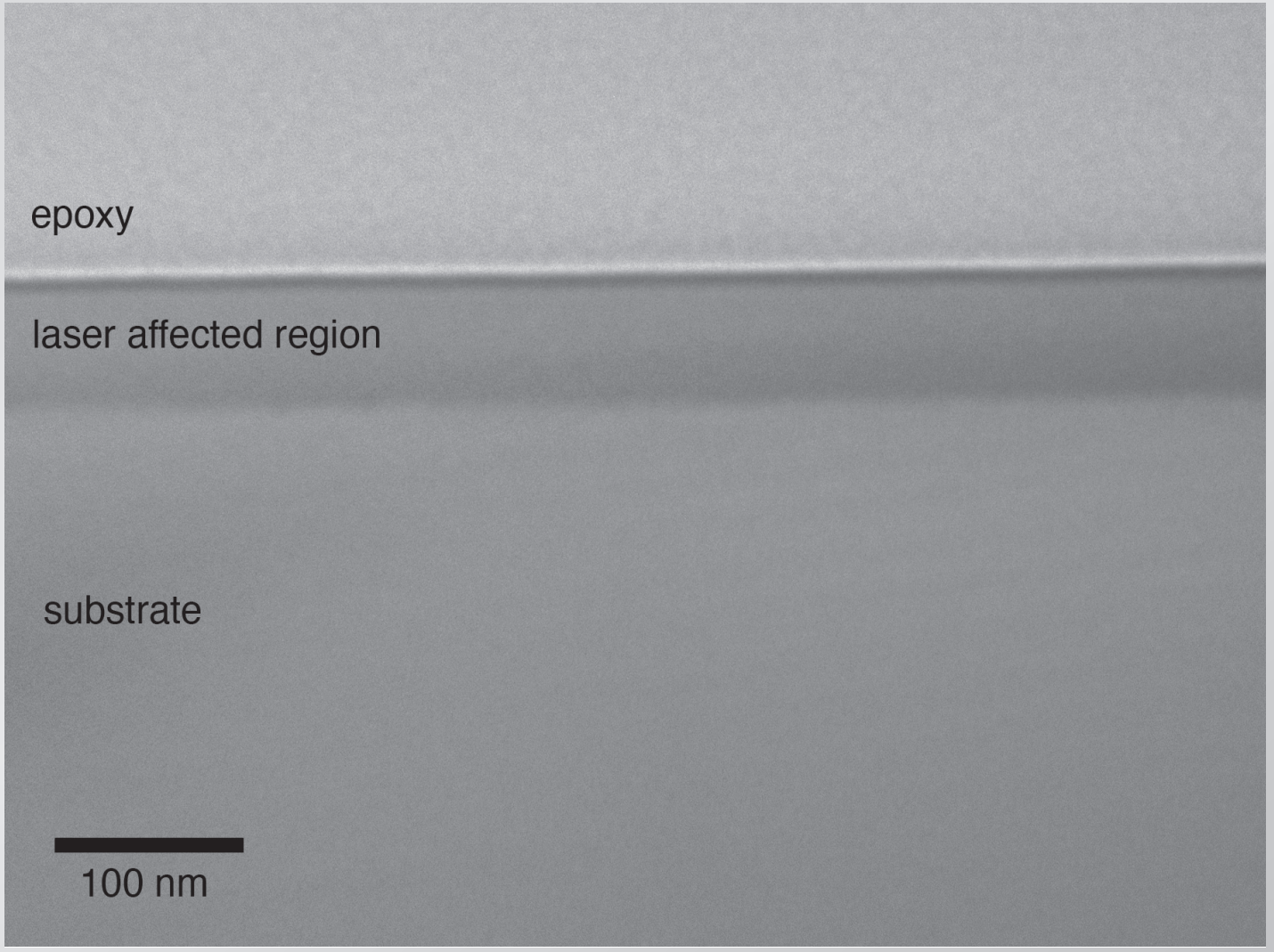

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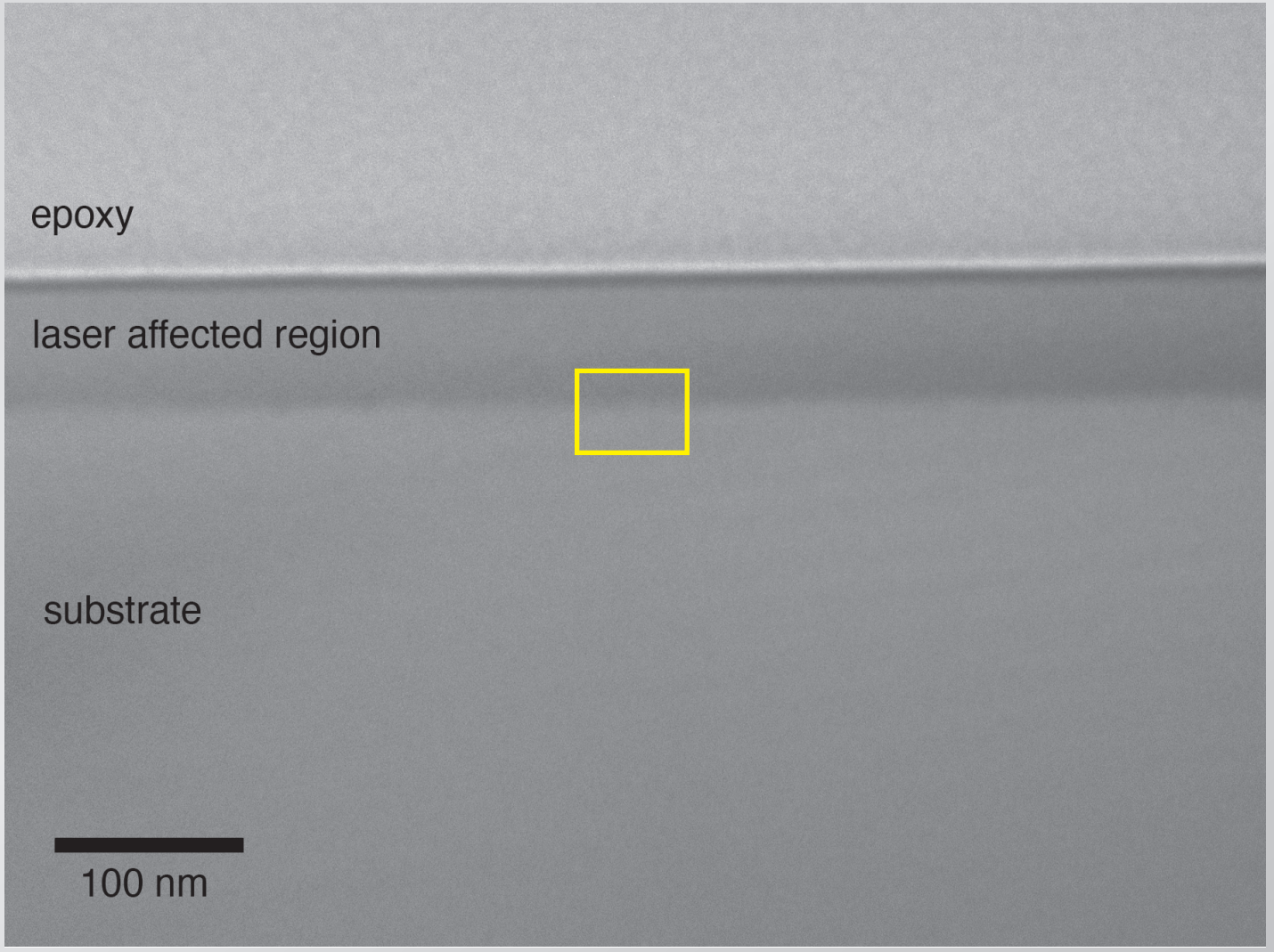

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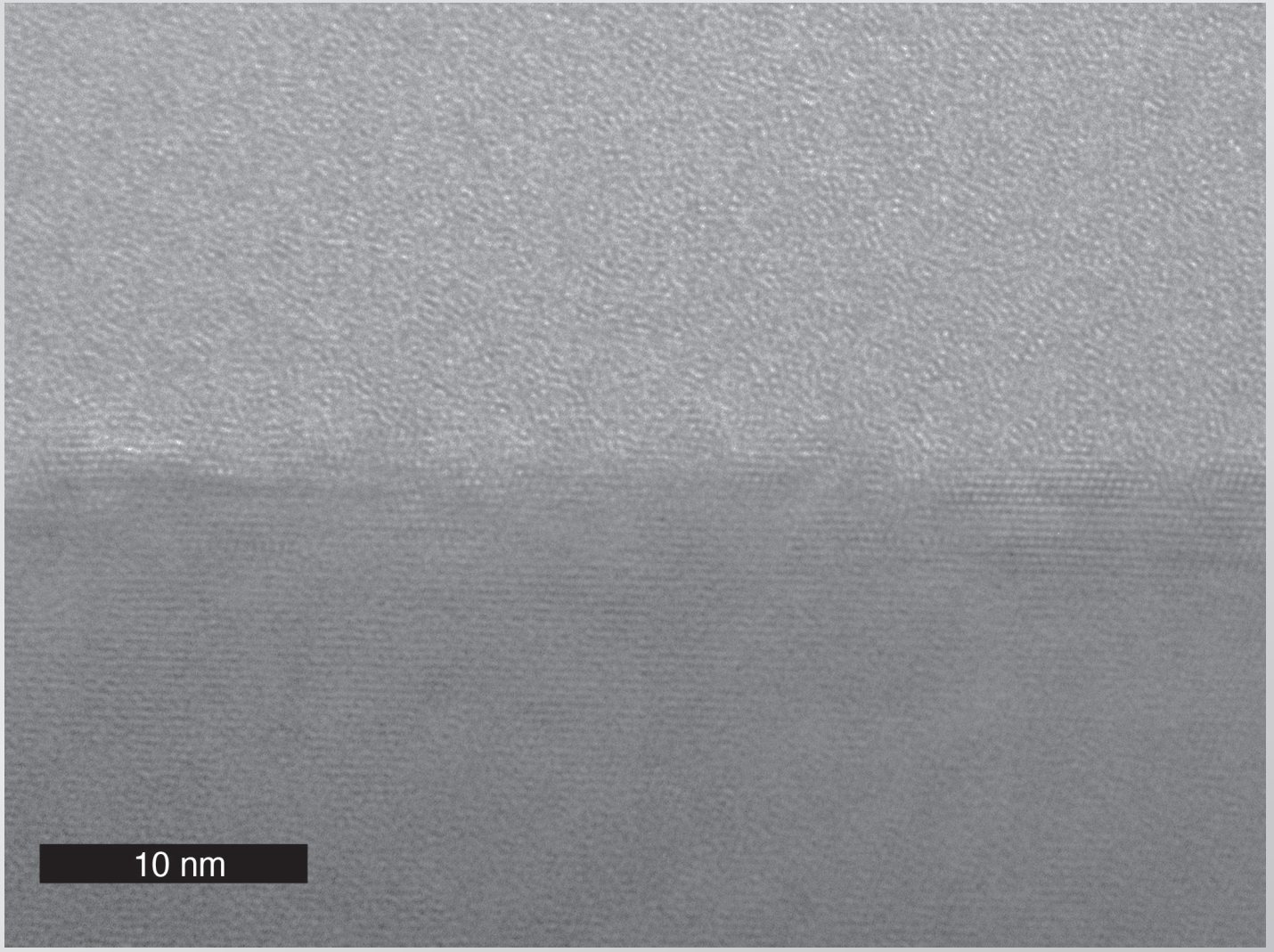

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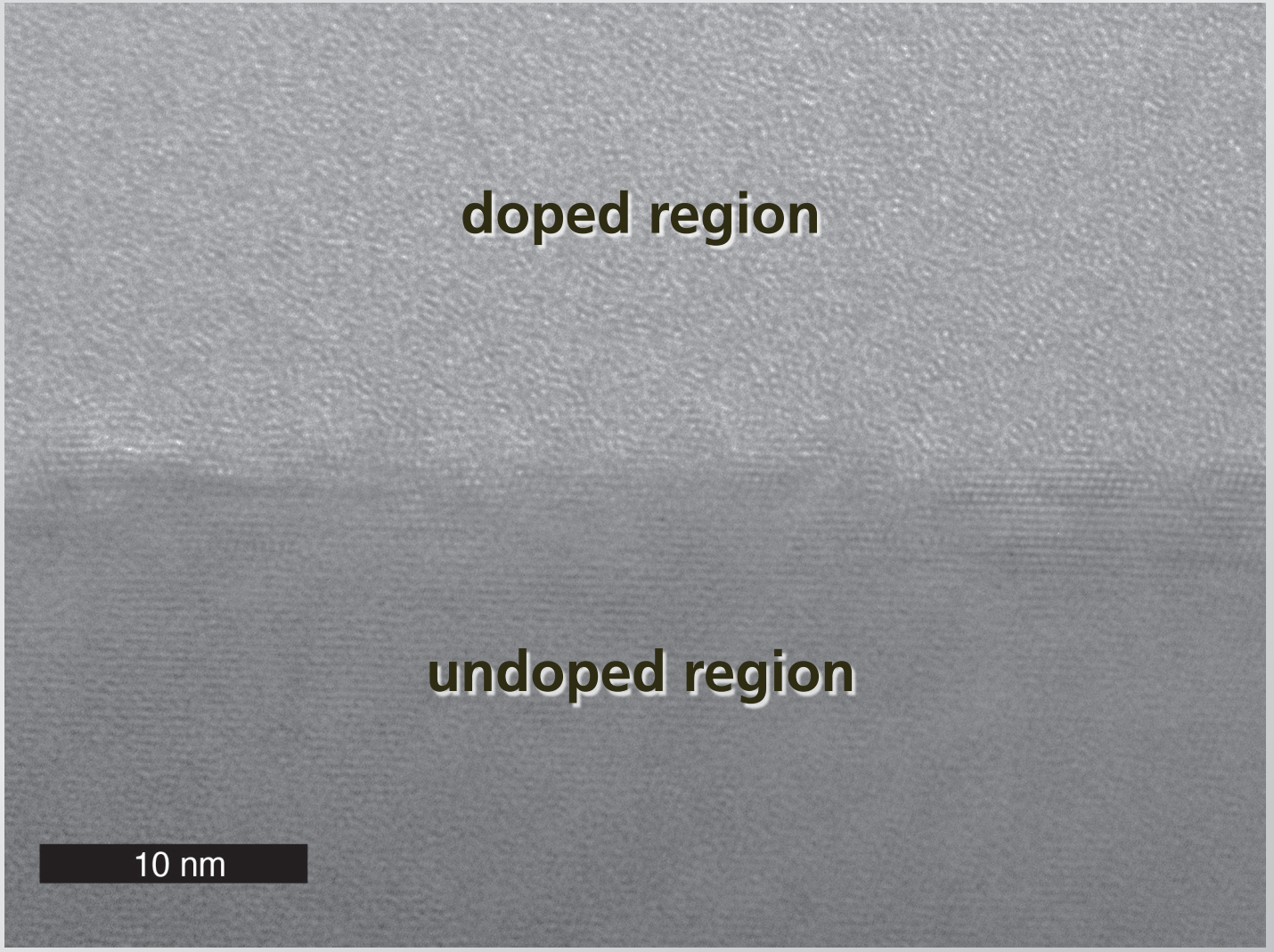
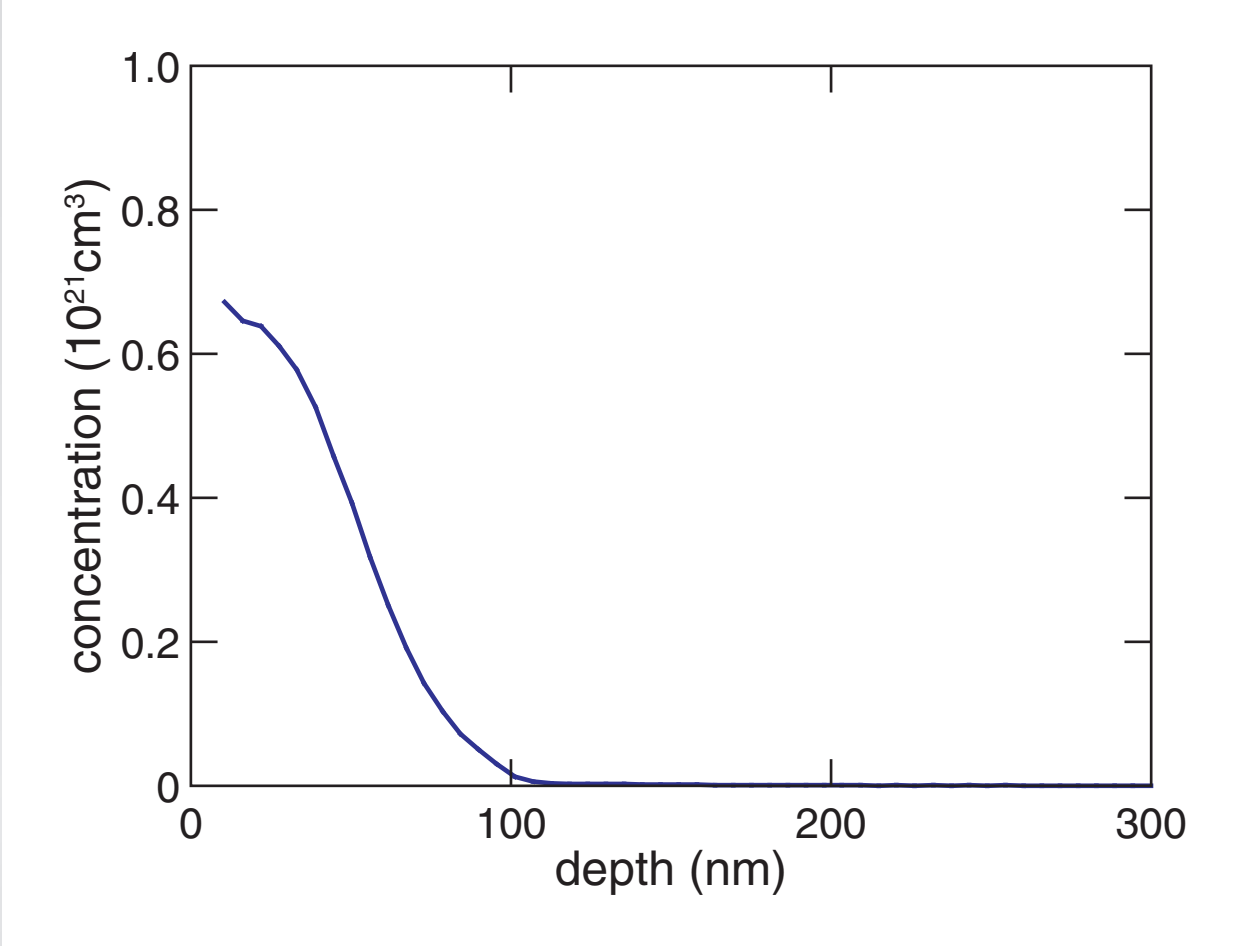


Structure

secondary ion mass spectrometry



Structure

Things to keep in mind

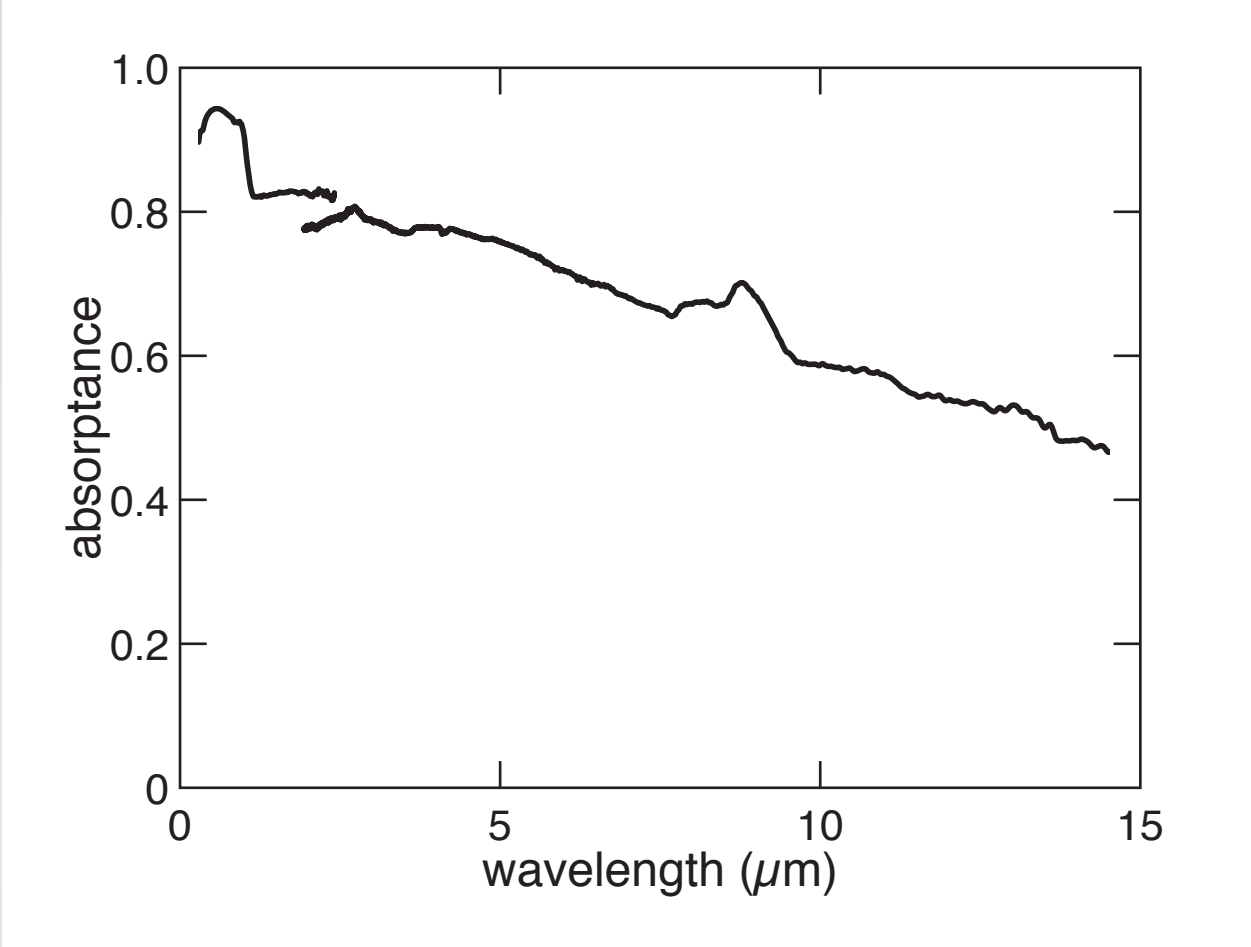
- rapid melting and resolidification causes doping
- ablation causes morphology changes
- about 1% impurity in 100-nm thick surface layer
- annealing changes impurity coordination

Outline

- structure
- optoelectronic properties
- devices

Optoelectronic properties

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



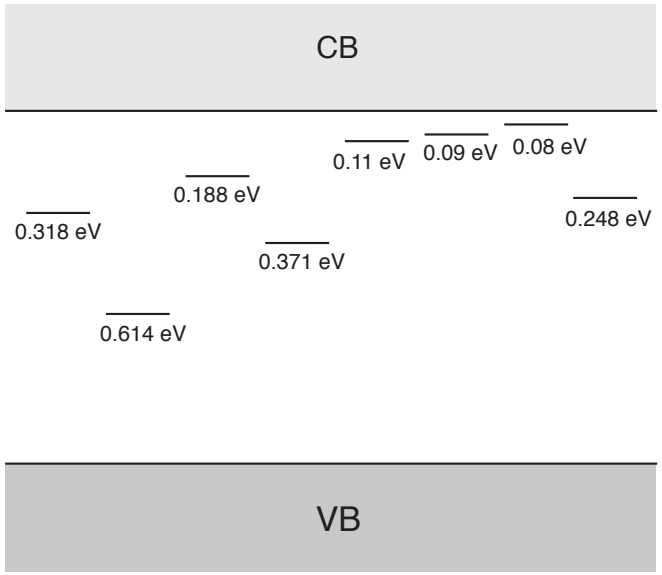
Asenbaum, Vienna

Optoelectronic properties

what dopant states/bands cause IR absorption?

Optoelectronic properties

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



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

Optoelectronic properties

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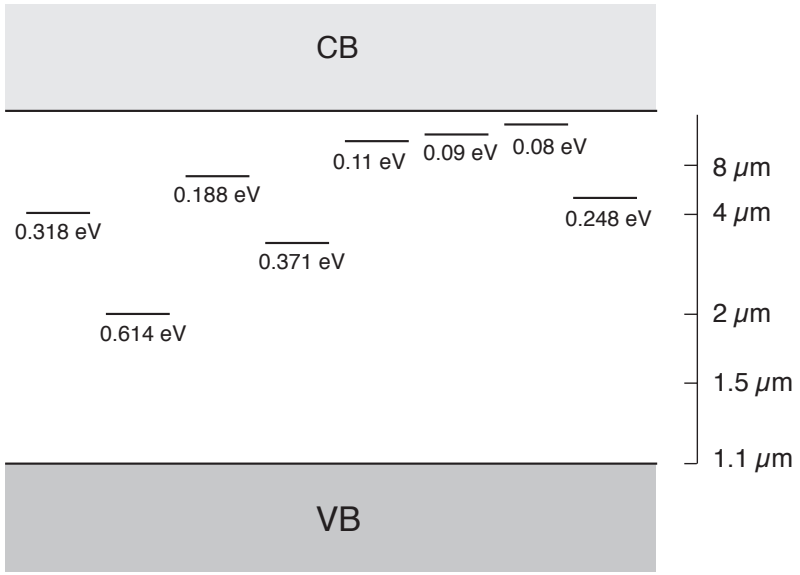

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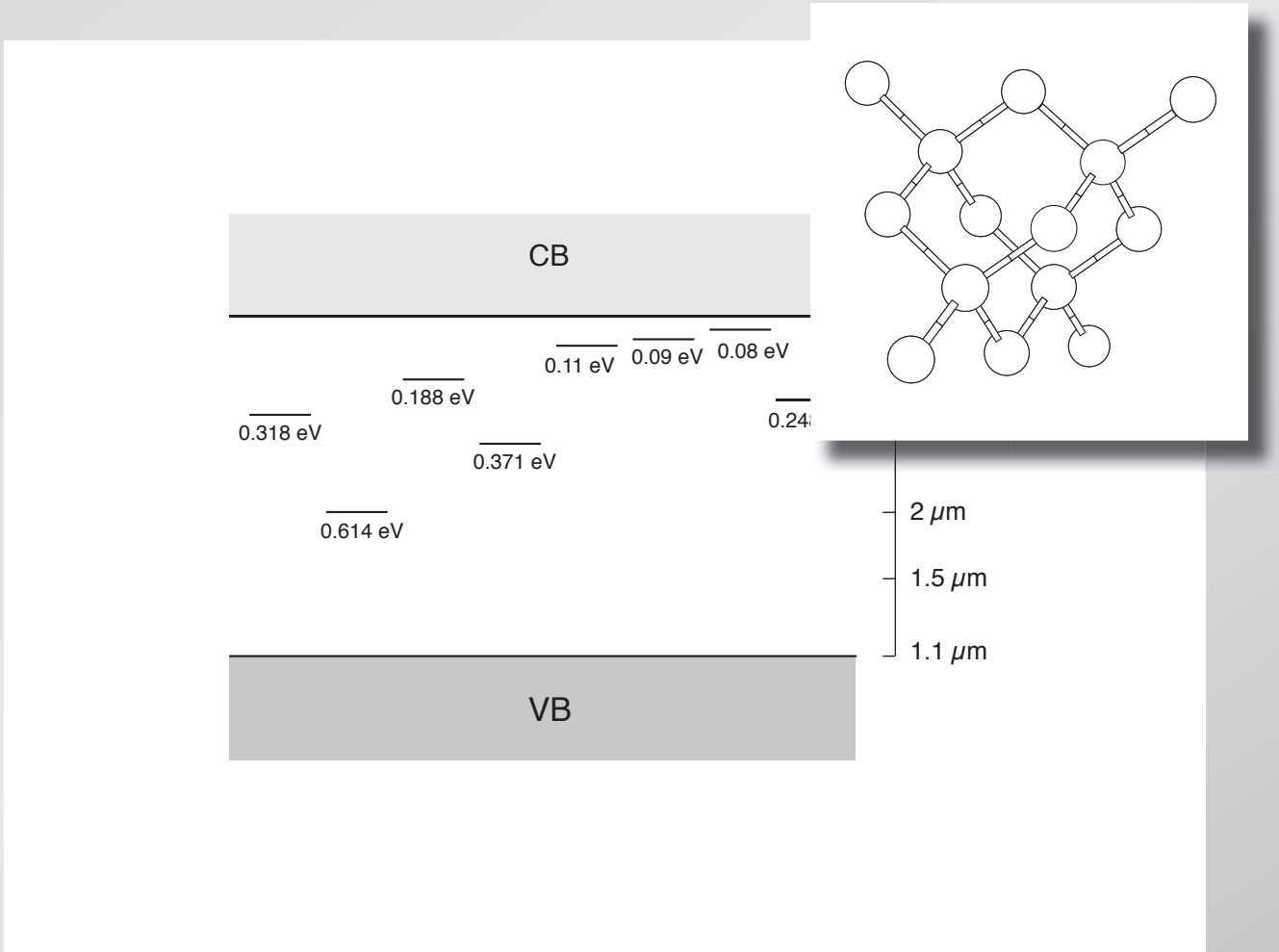

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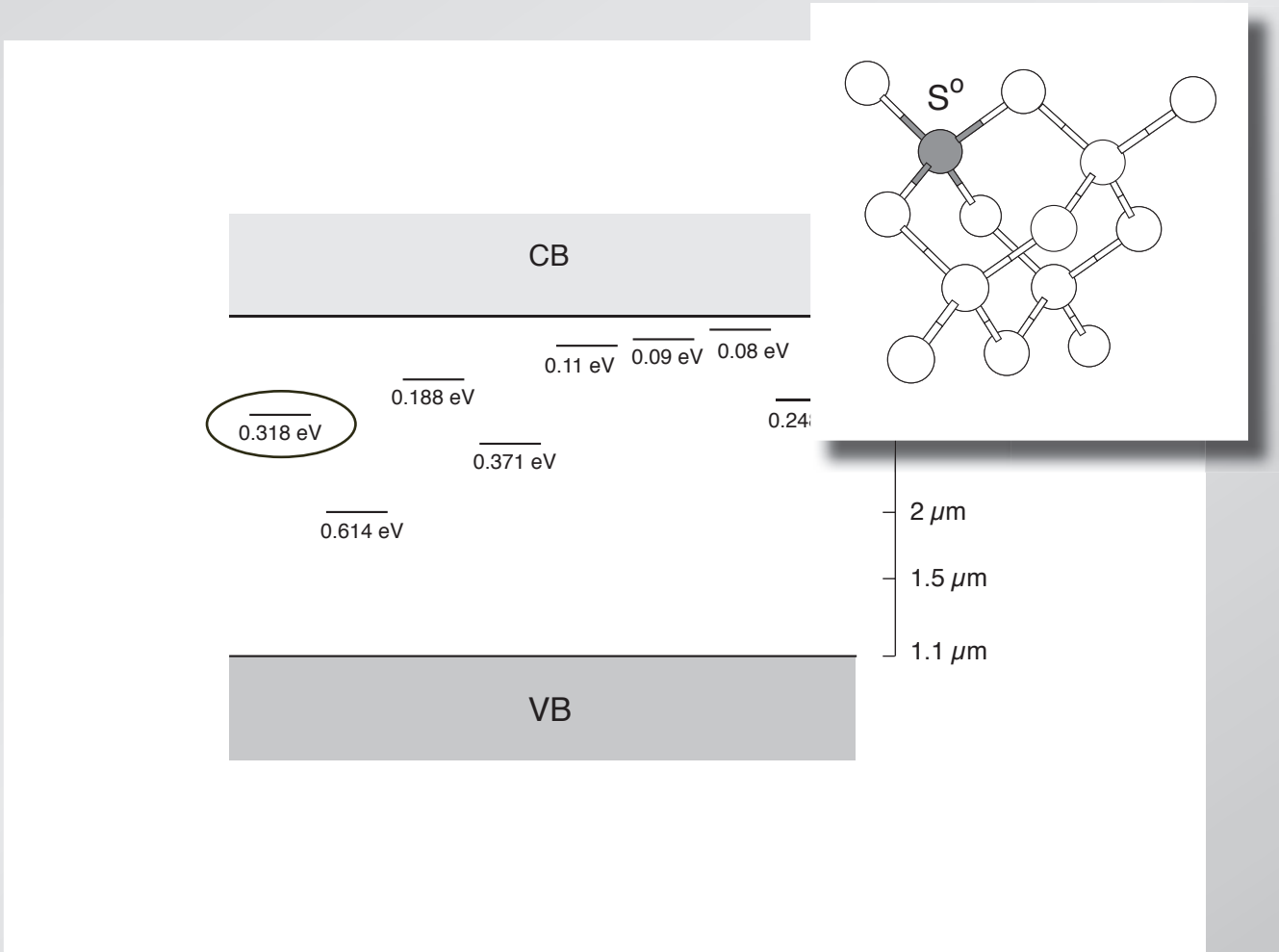

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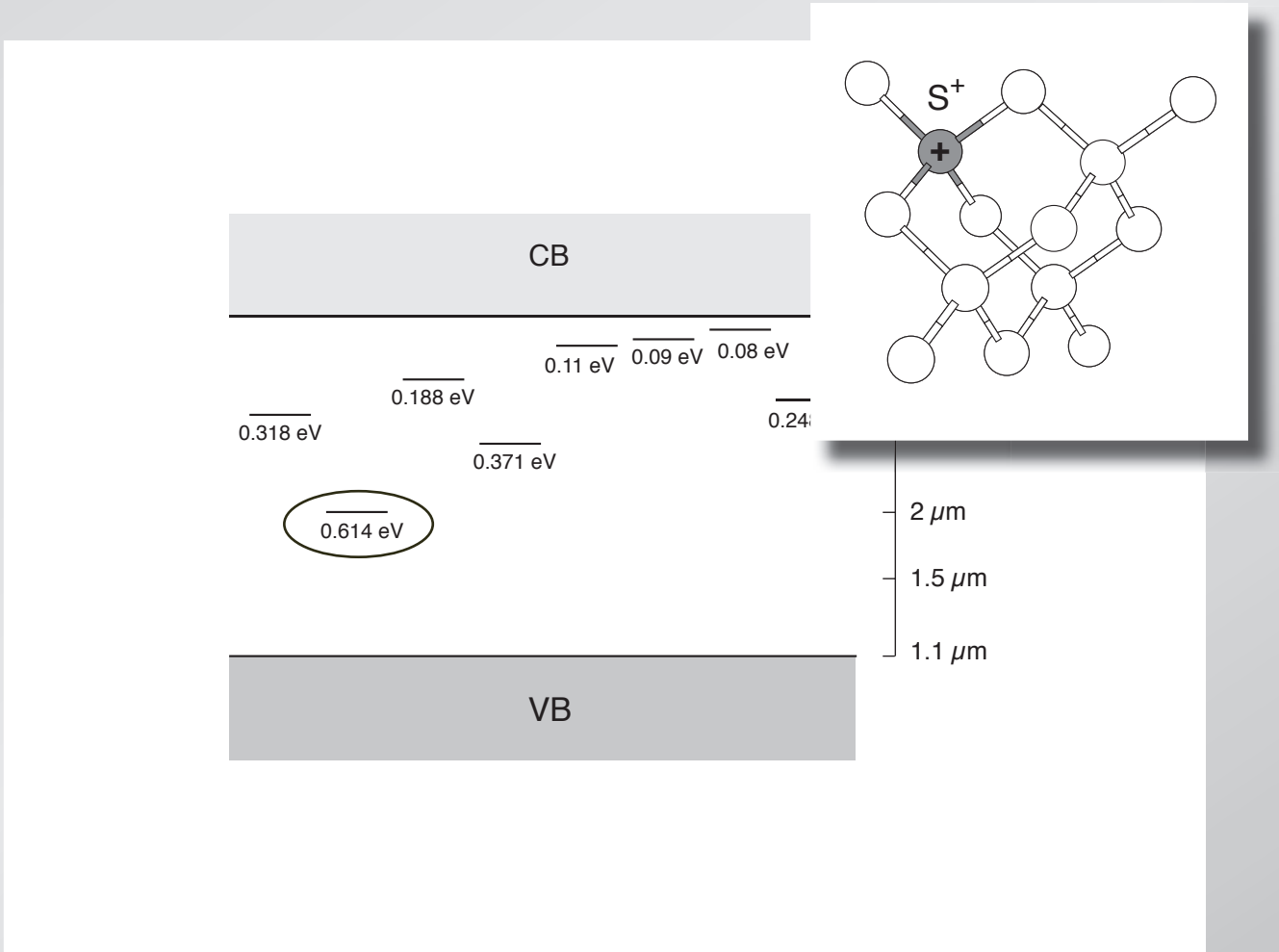

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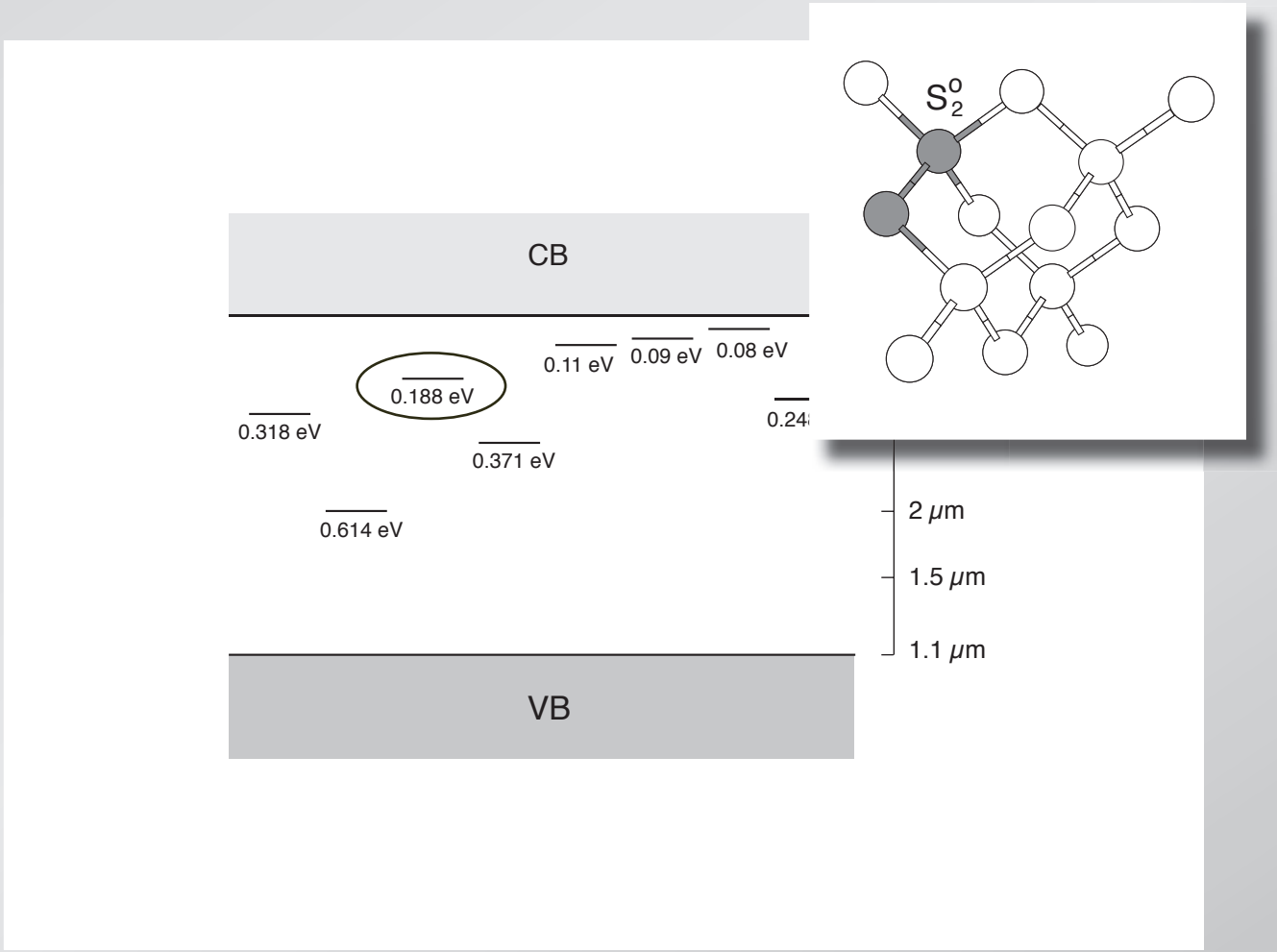

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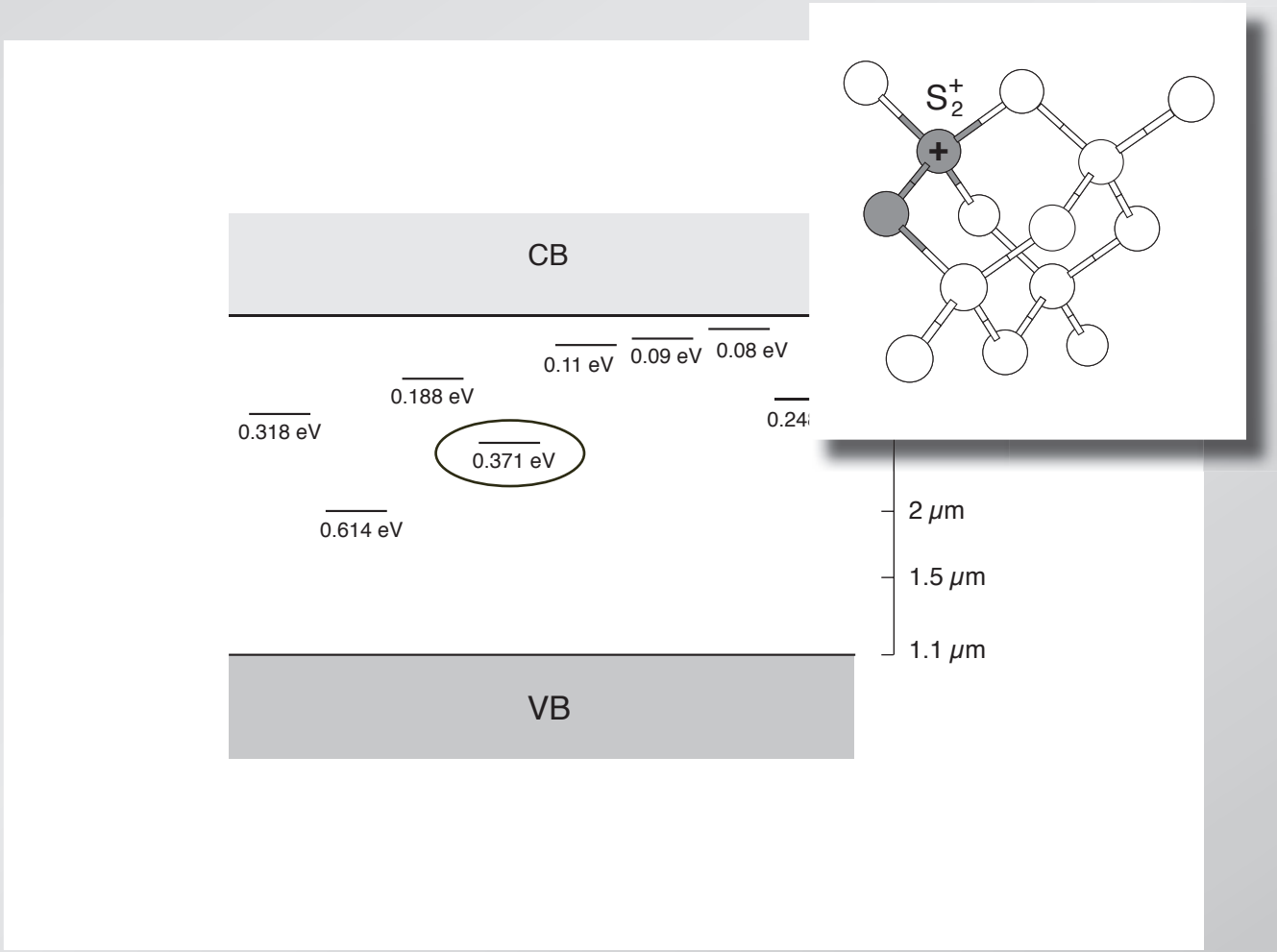

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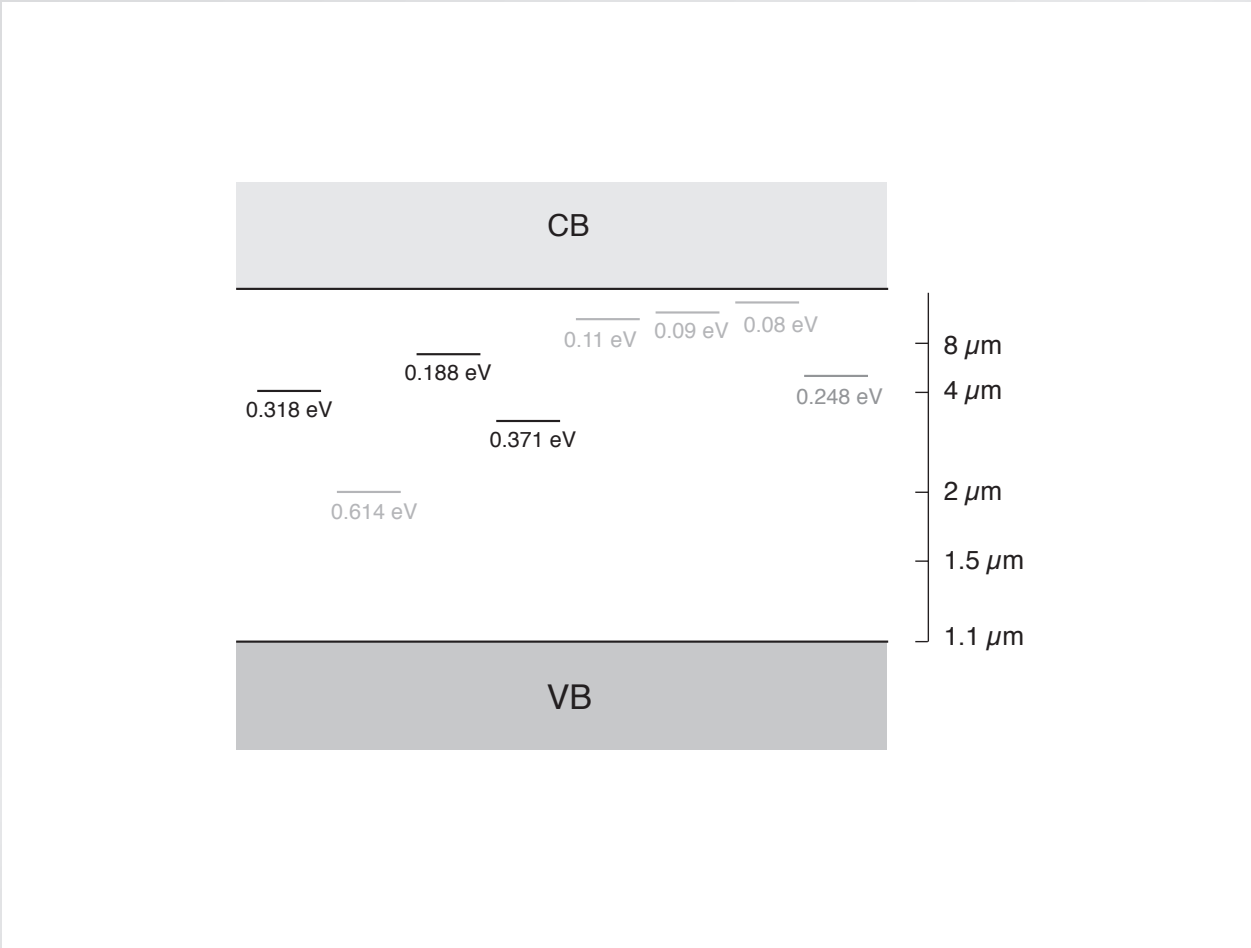
Optoelectronic properties

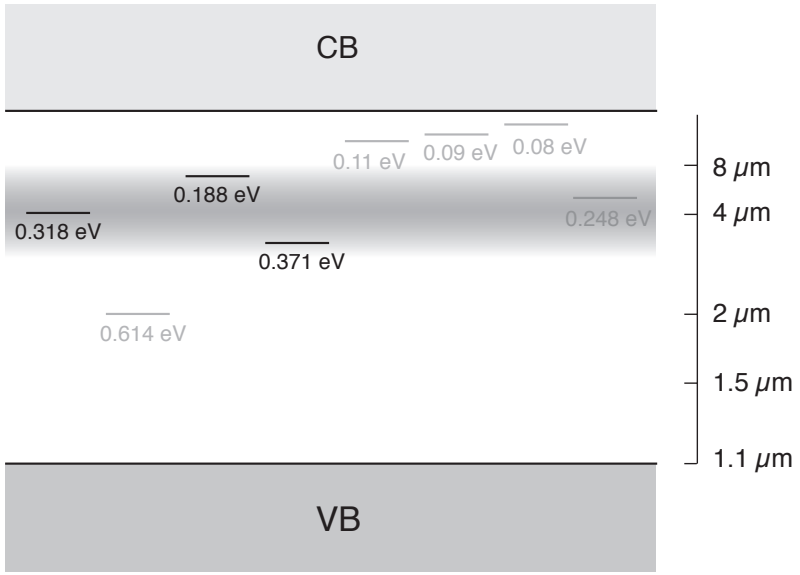
1 part in 10^6 sulfur introduces donor states in gap



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

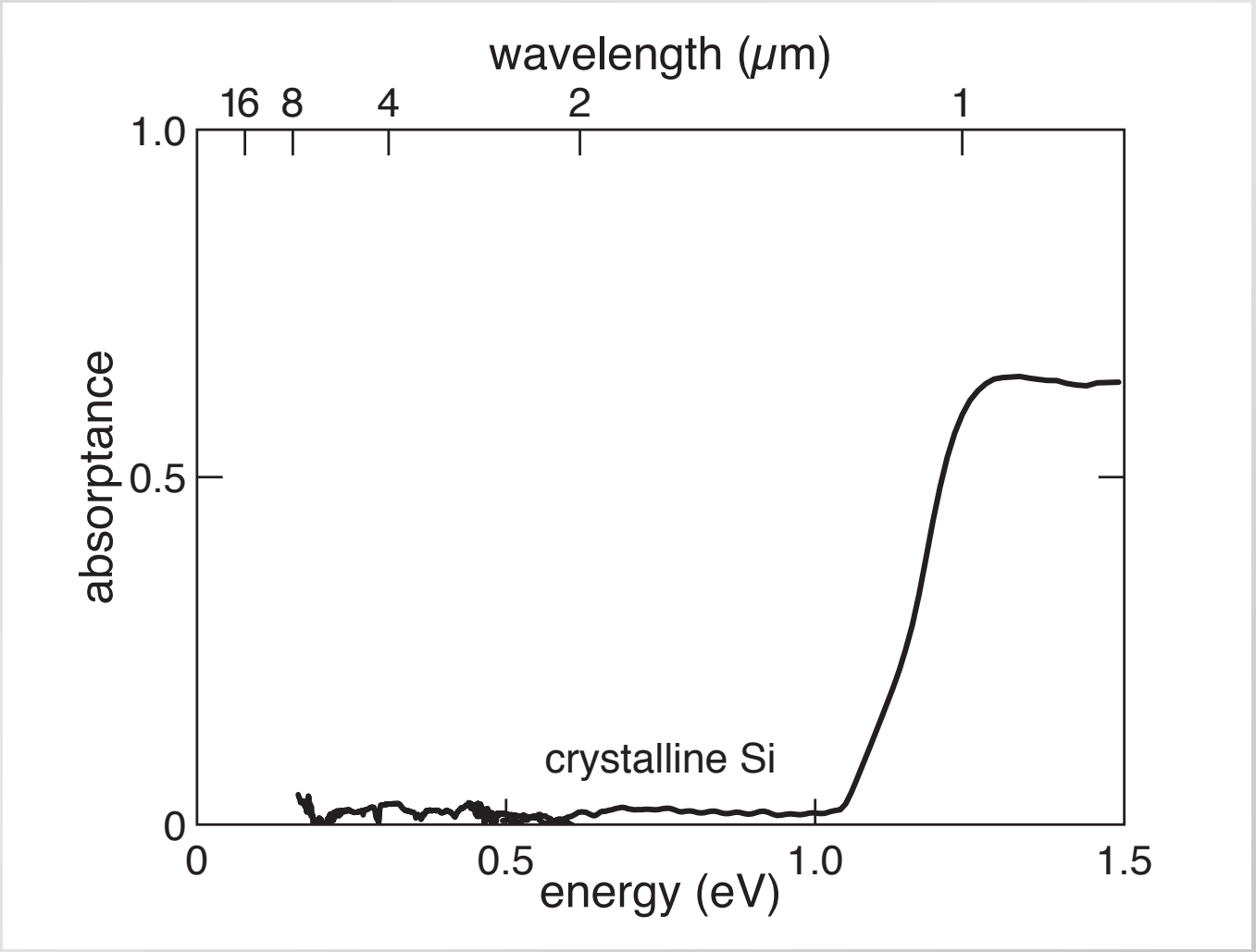
Optoelectronic properties

at high concentration states broaden into band



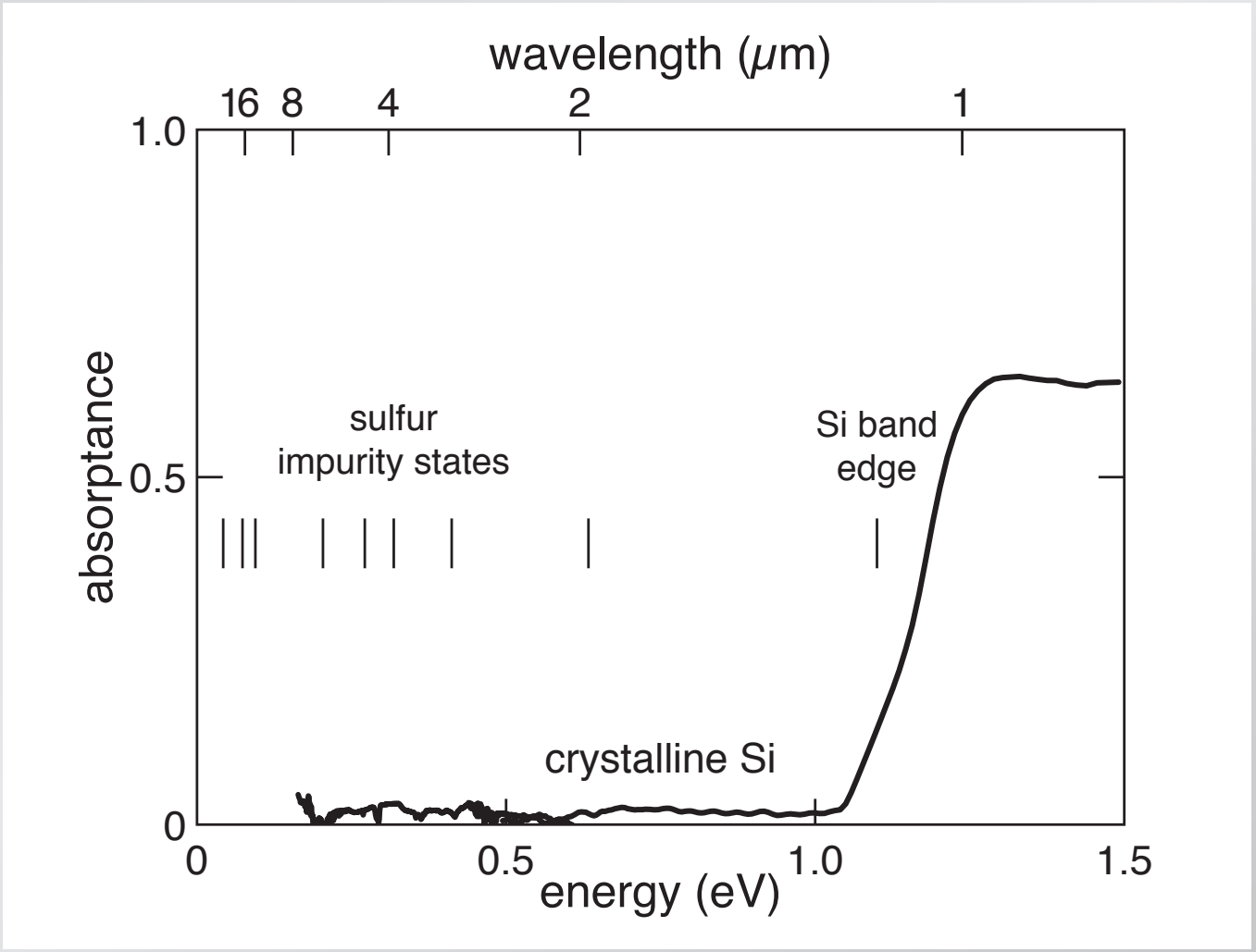
Optoelectronic properties

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



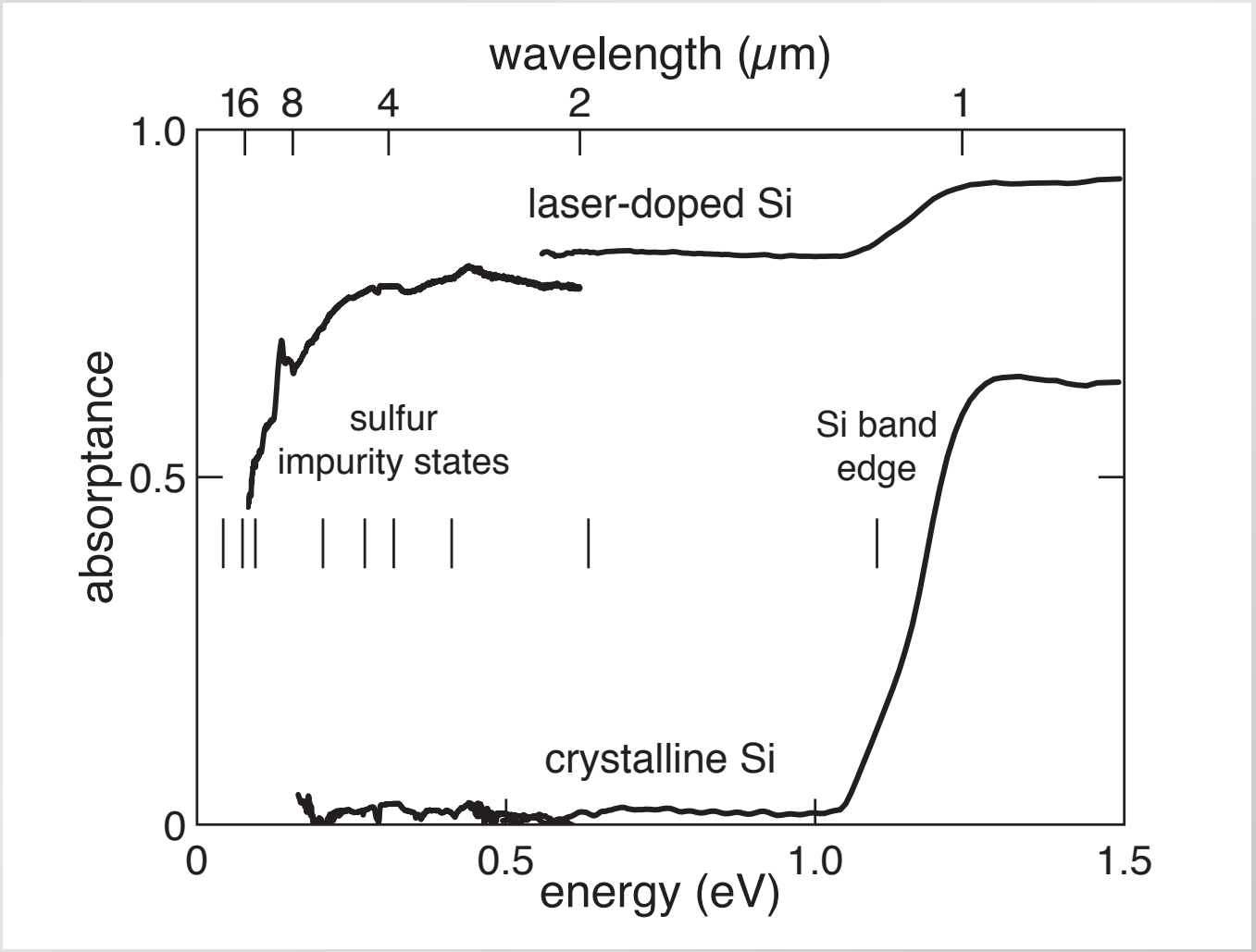
Optoelectronic properties

10^{-6} sulfur doping



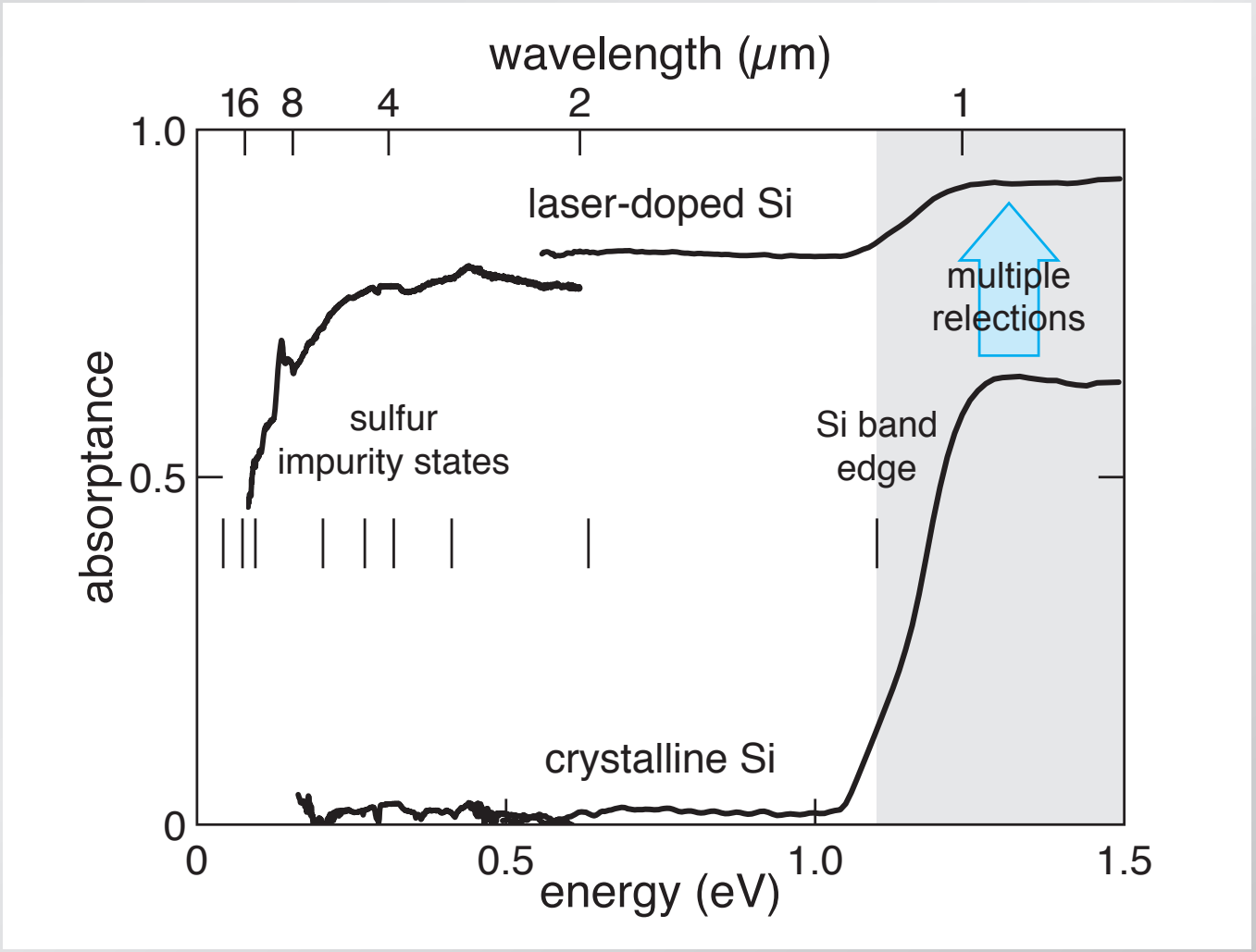
Optoelectronic properties

laser-doped S:Si



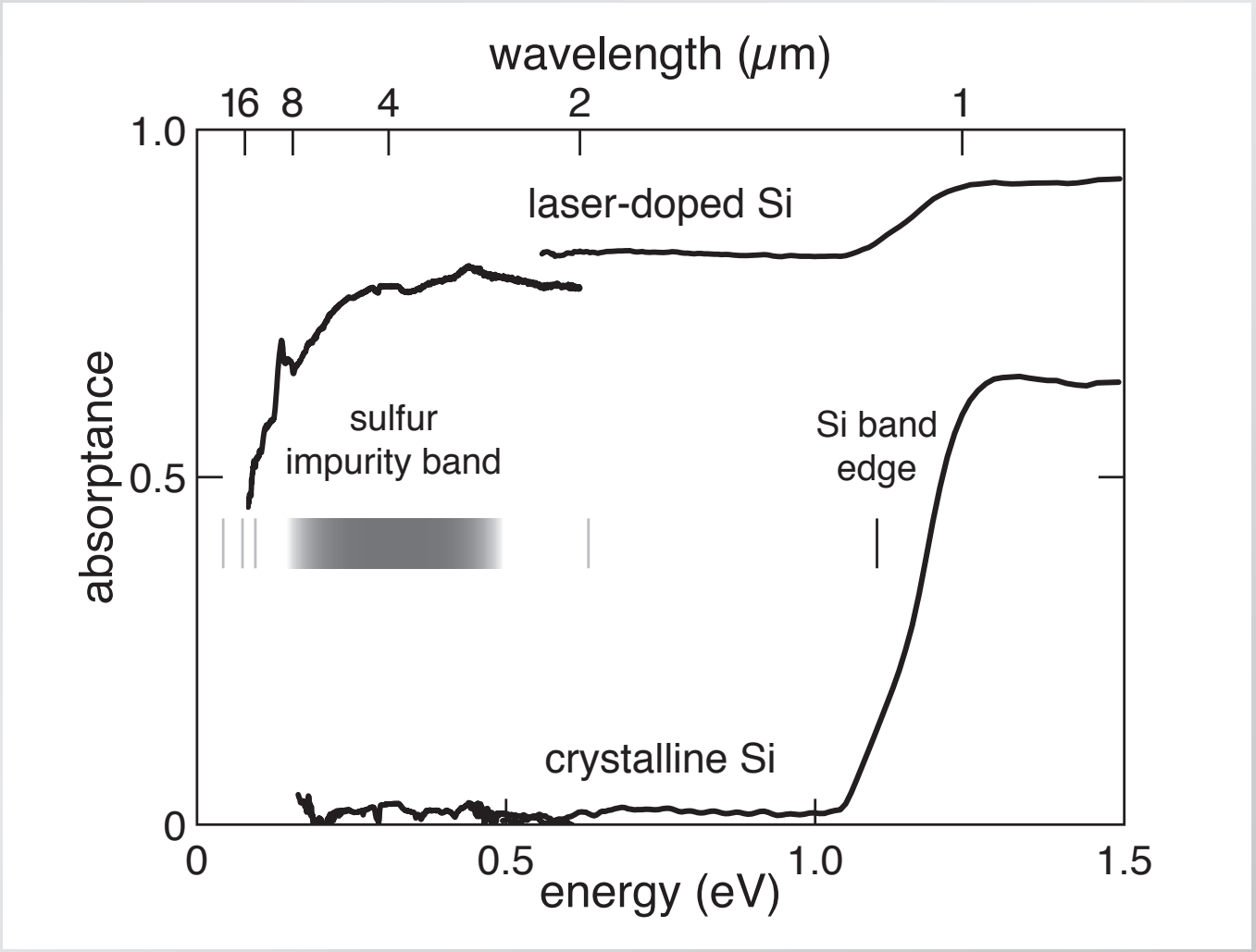
Optoelectronic properties

laser-doped S:Si



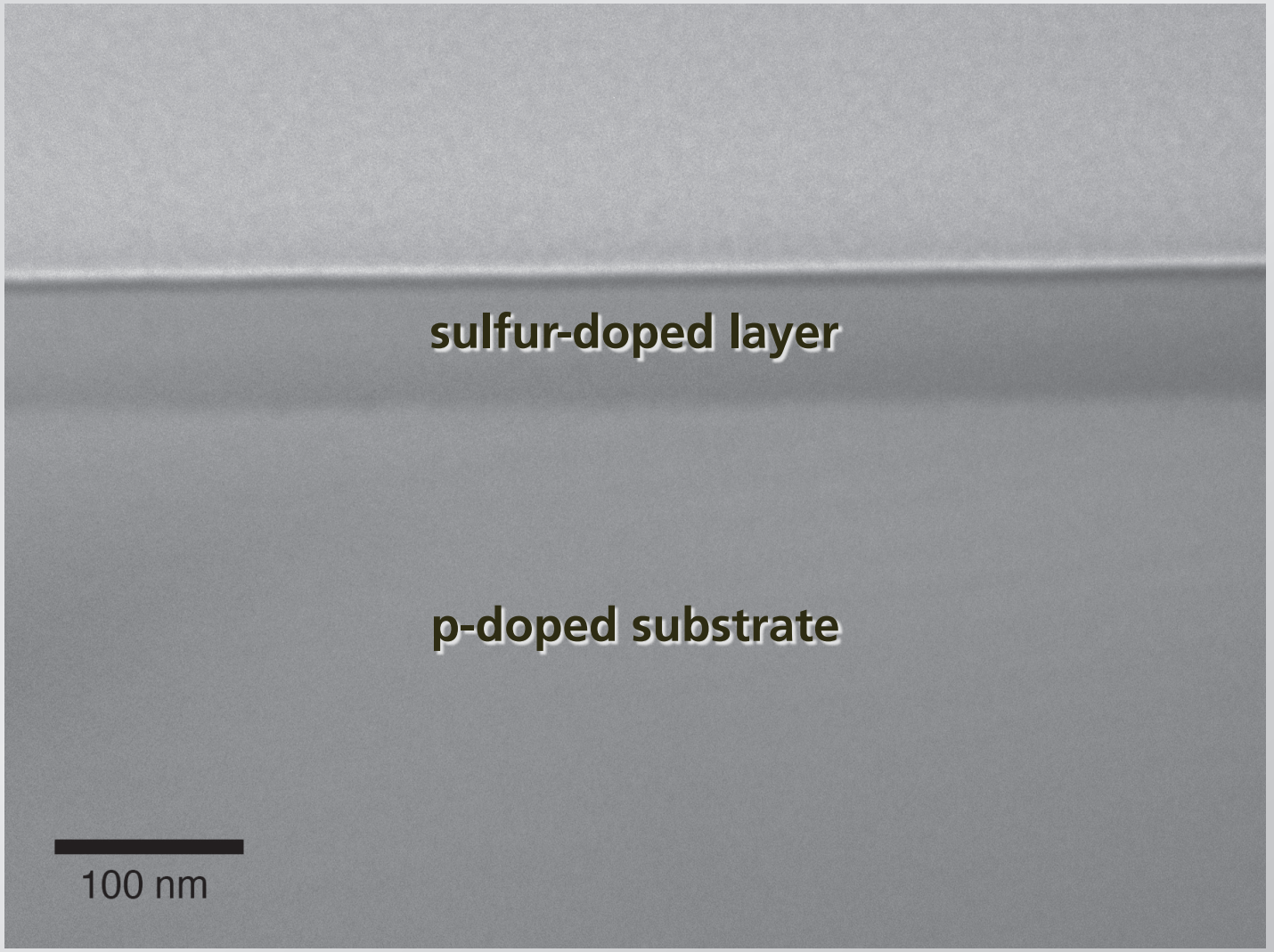
Optoelectronic properties

laser-doped S:Si



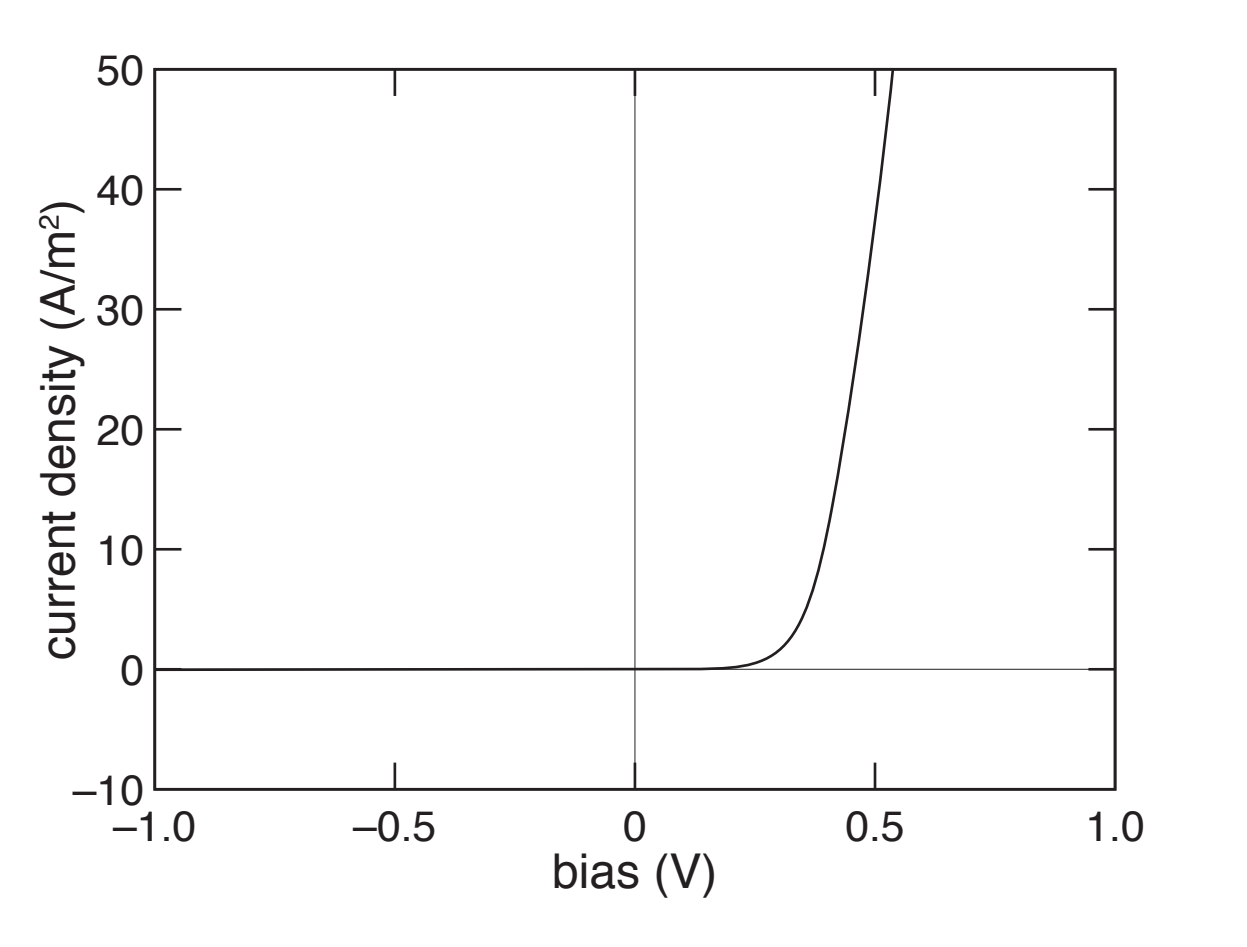
Optoelectronic properties

should have shallow junction below surface



Optoelectronic properties

excellent rectification (after annealing)



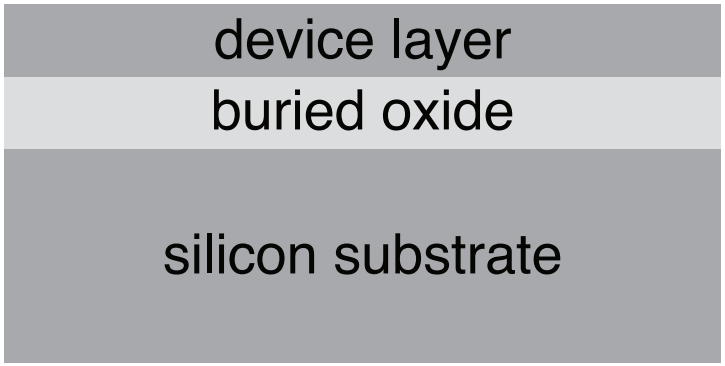
Optoelectronic properties

IV **behavior consistent with**

impurity band between 200 and 400 meV

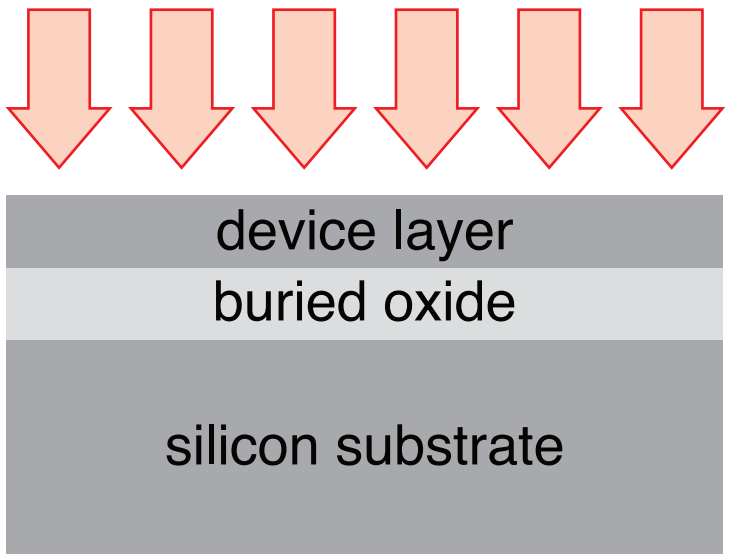
Optoelectronic properties

isolate surface layer for Hall measurements



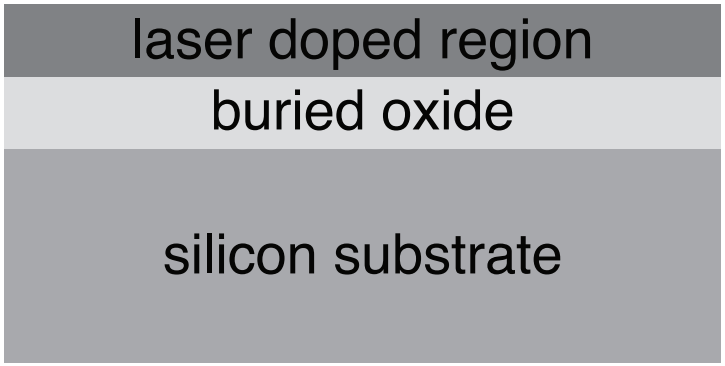
Optoelectronic properties

isolate surface layer for Hall measurements



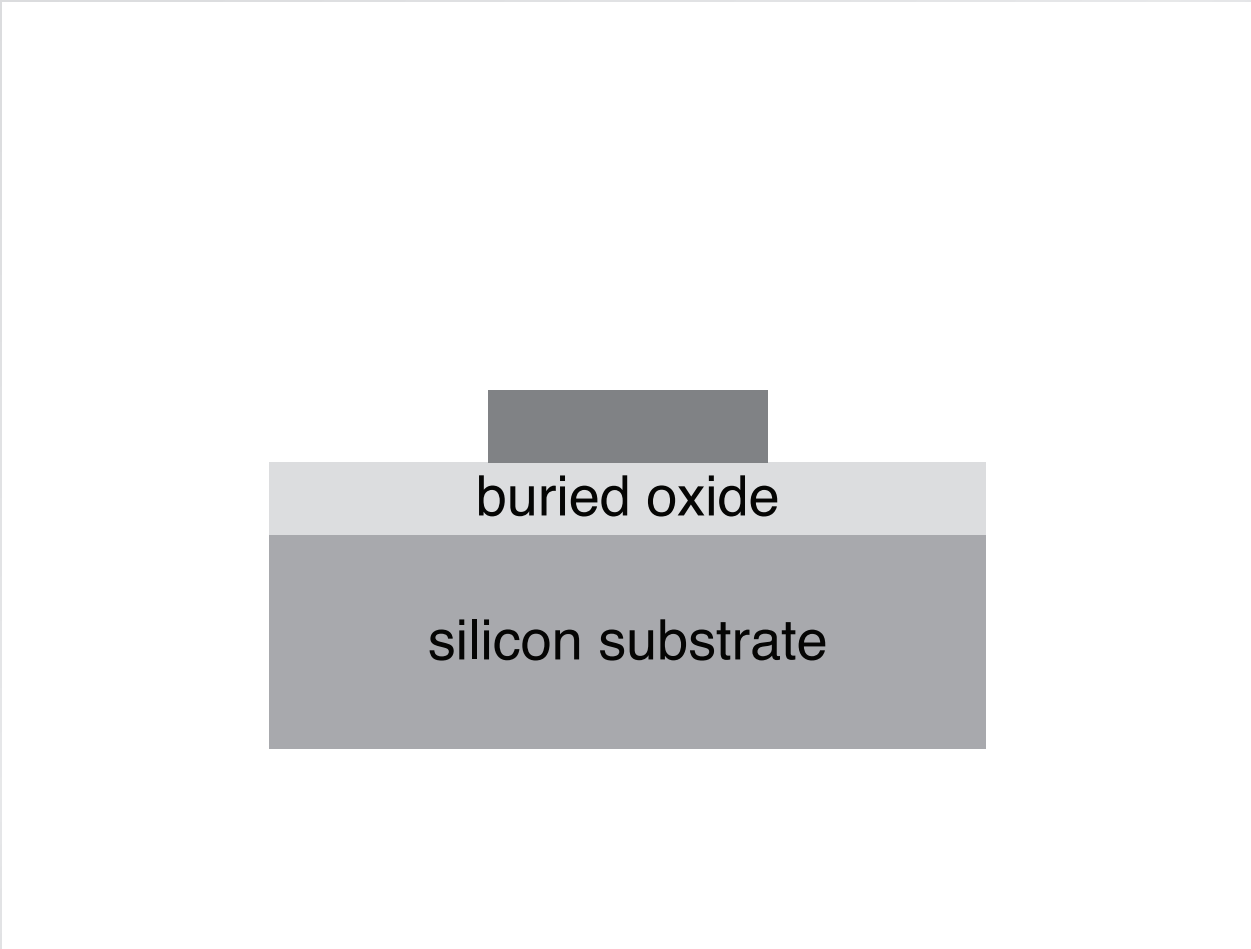
Optoelectronic properties

isolate surface layer for Hall measurements



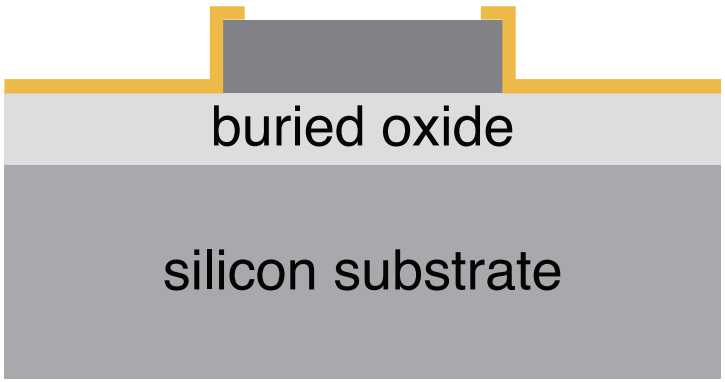
Optoelectronic properties

isolate surface layer for Hall measurements

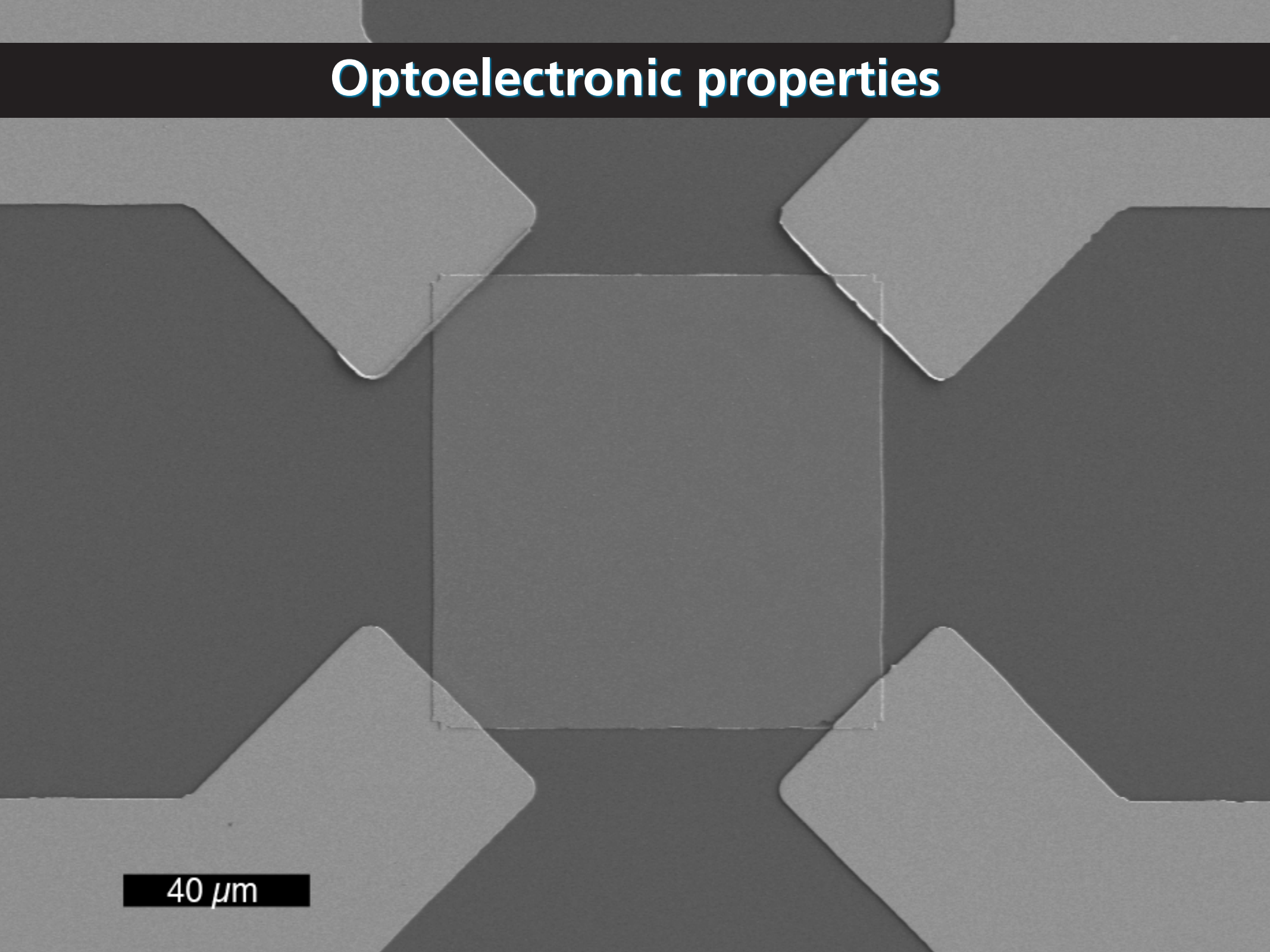


Optoelectronic properties

isolate surface layer for Hall measurements

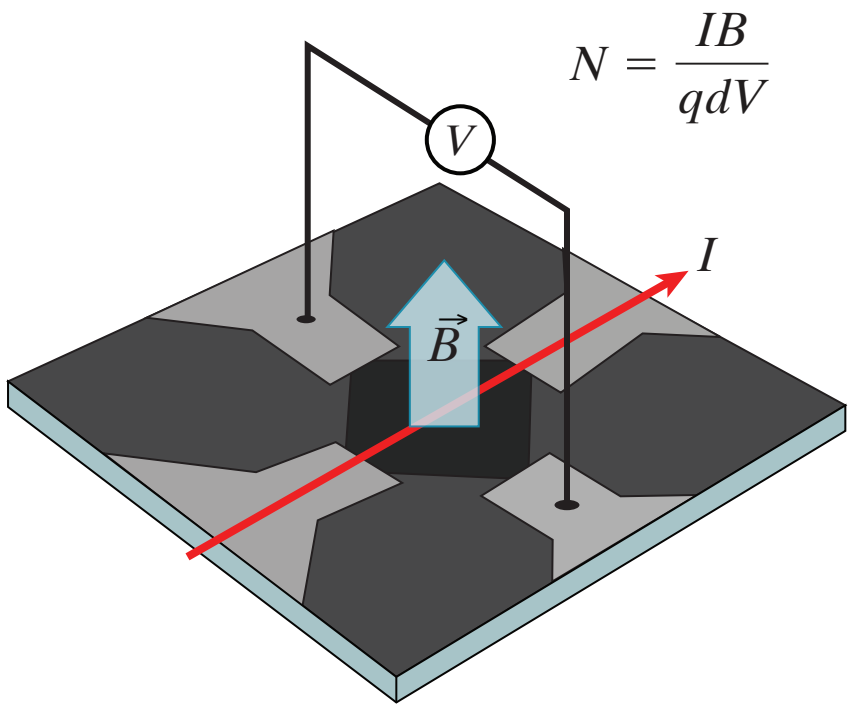


Optoelectronic properties



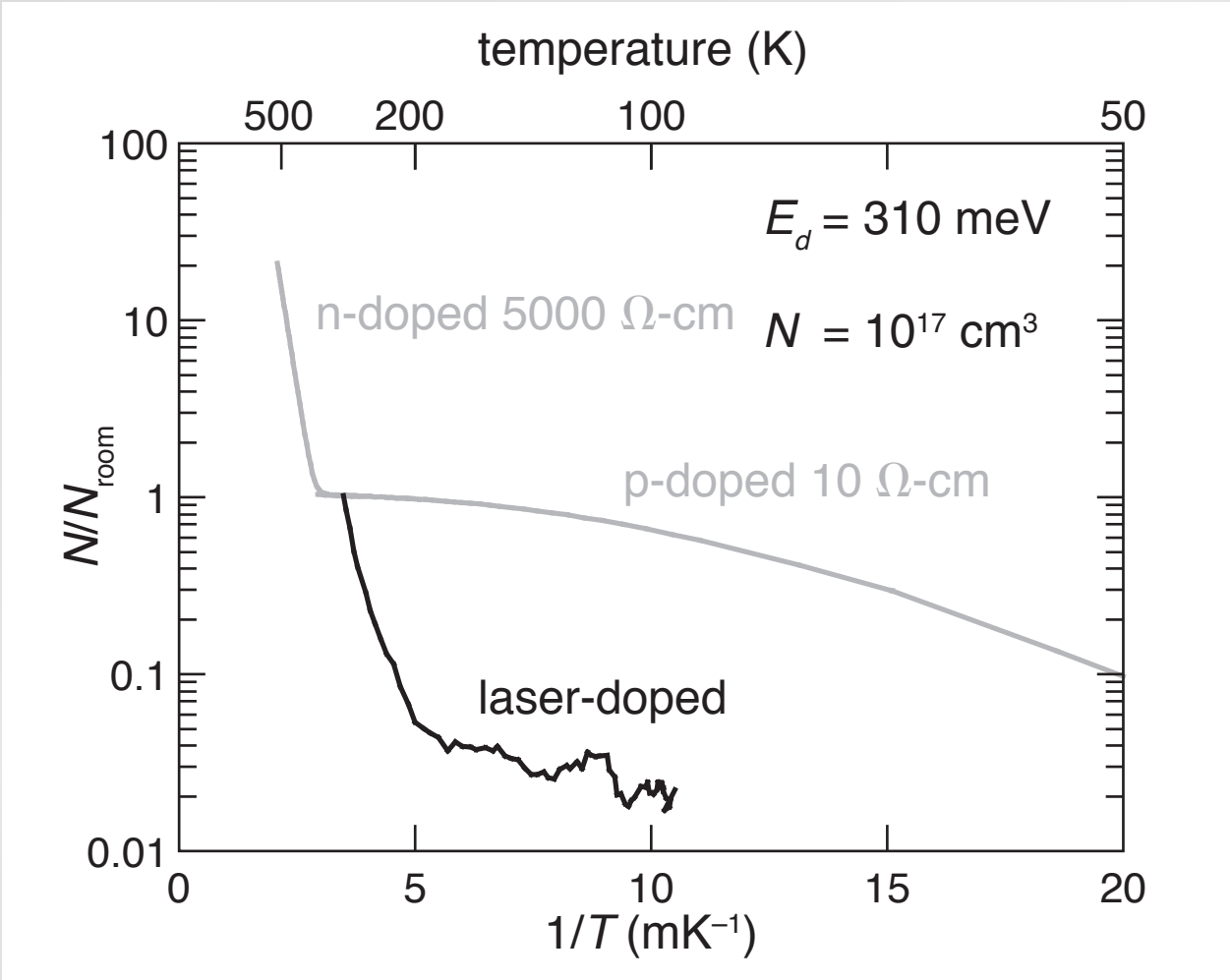
Optoelectronic properties

Hall measurements



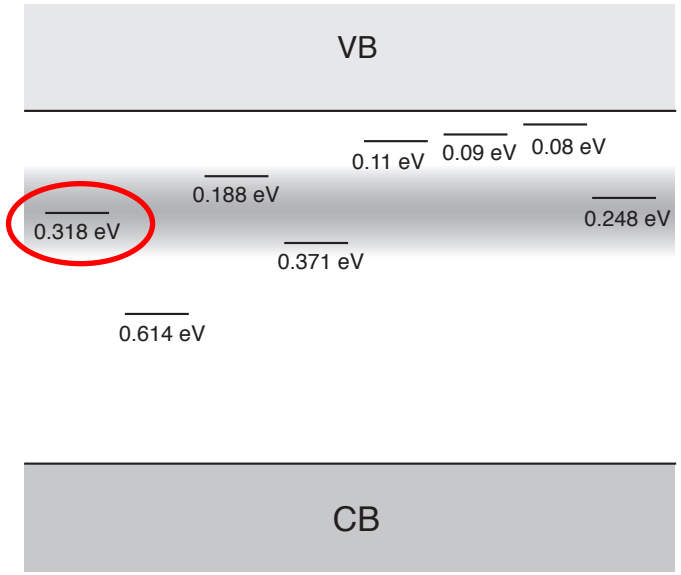
Optoelectronic properties

Hall measurements



Optoelectronic properties

impurity (donor) band centered at 310 meV

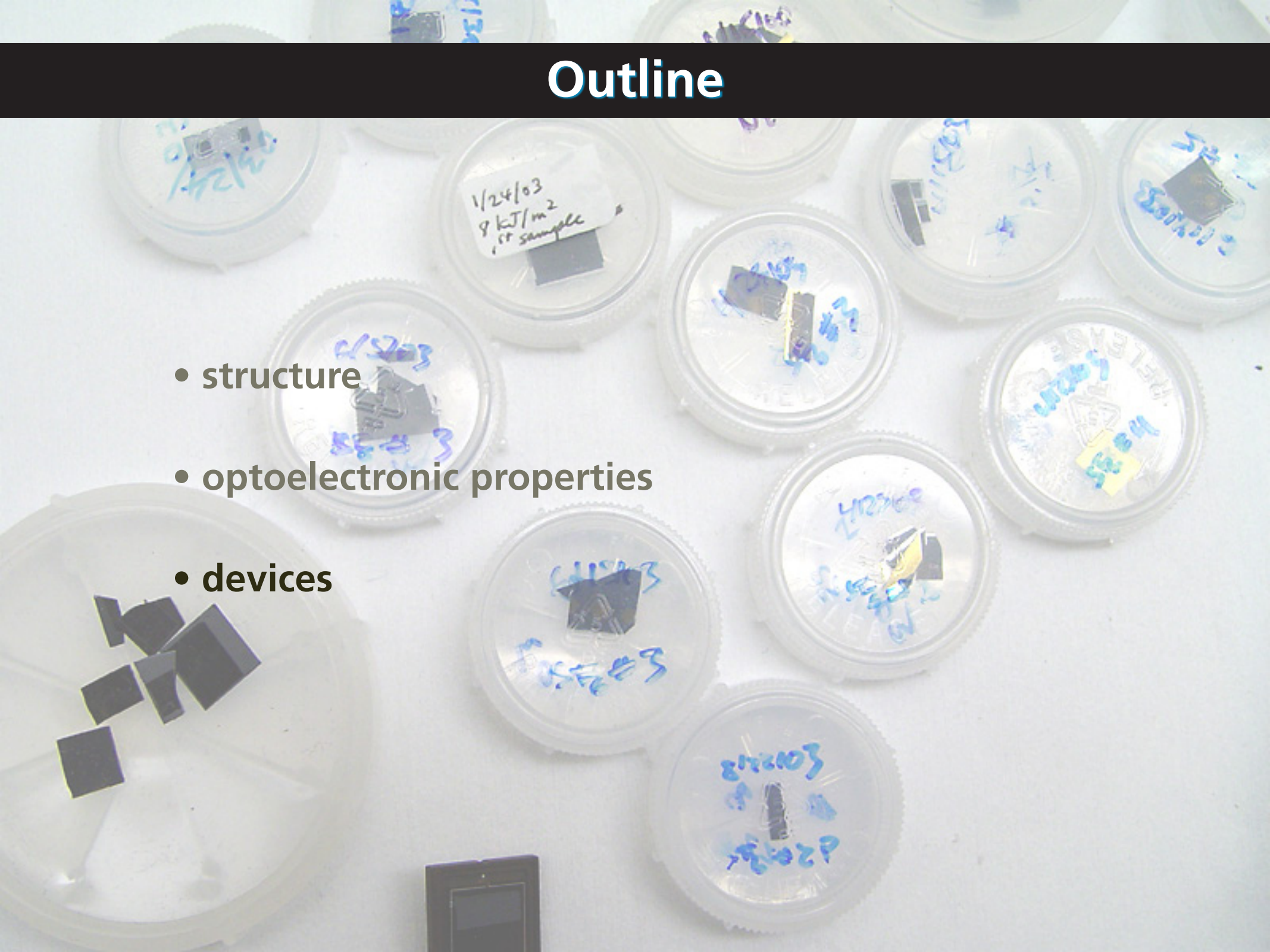


Optoelectronic properties

Things to keep in mind

- IR absorption rolls off around 8 μm
- 1 in 10^3 sulfur atoms are ionized donors at 300 K
- all data indicate these S donors are substitutional

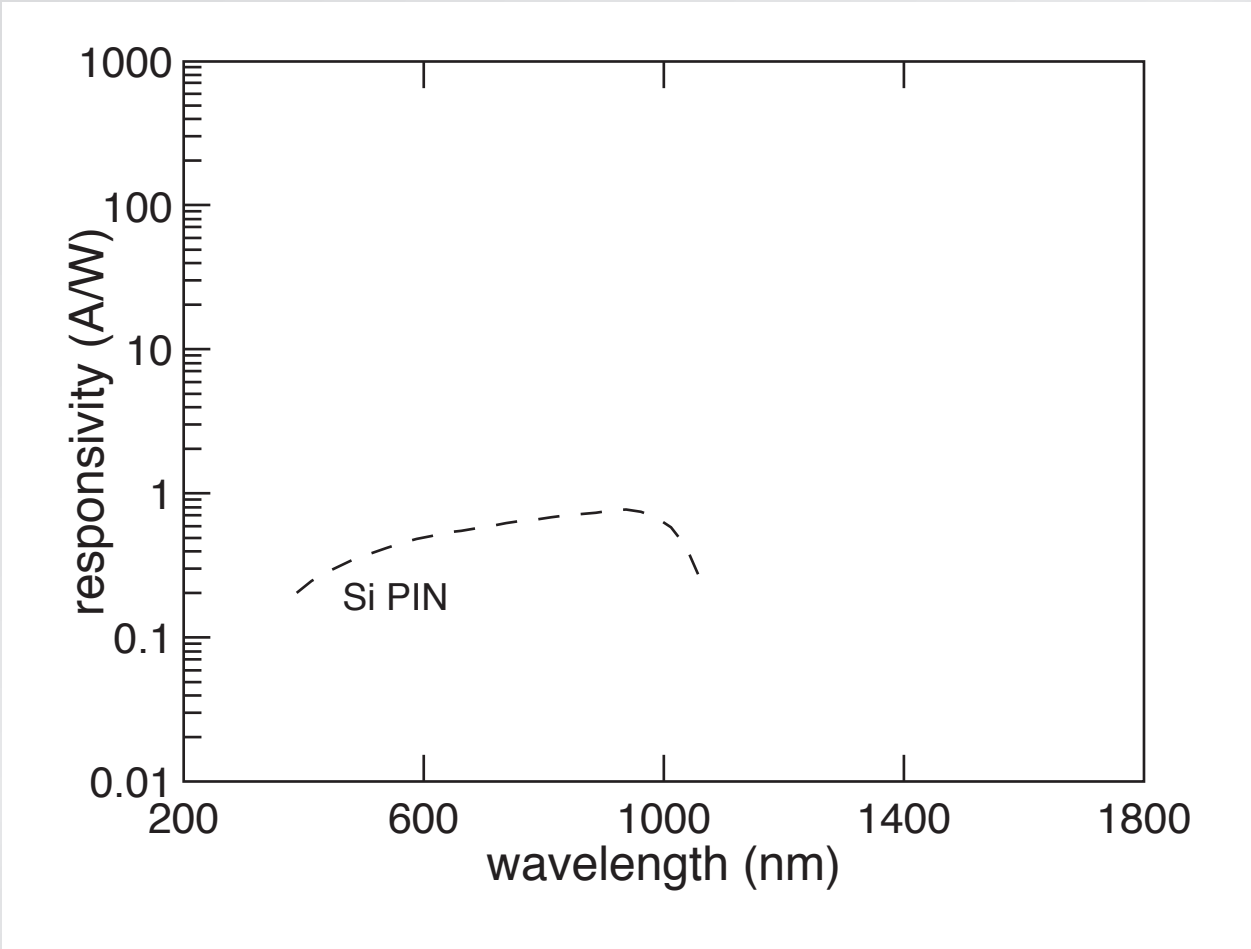
Outline



- structure
- optoelectronic properties
- devices

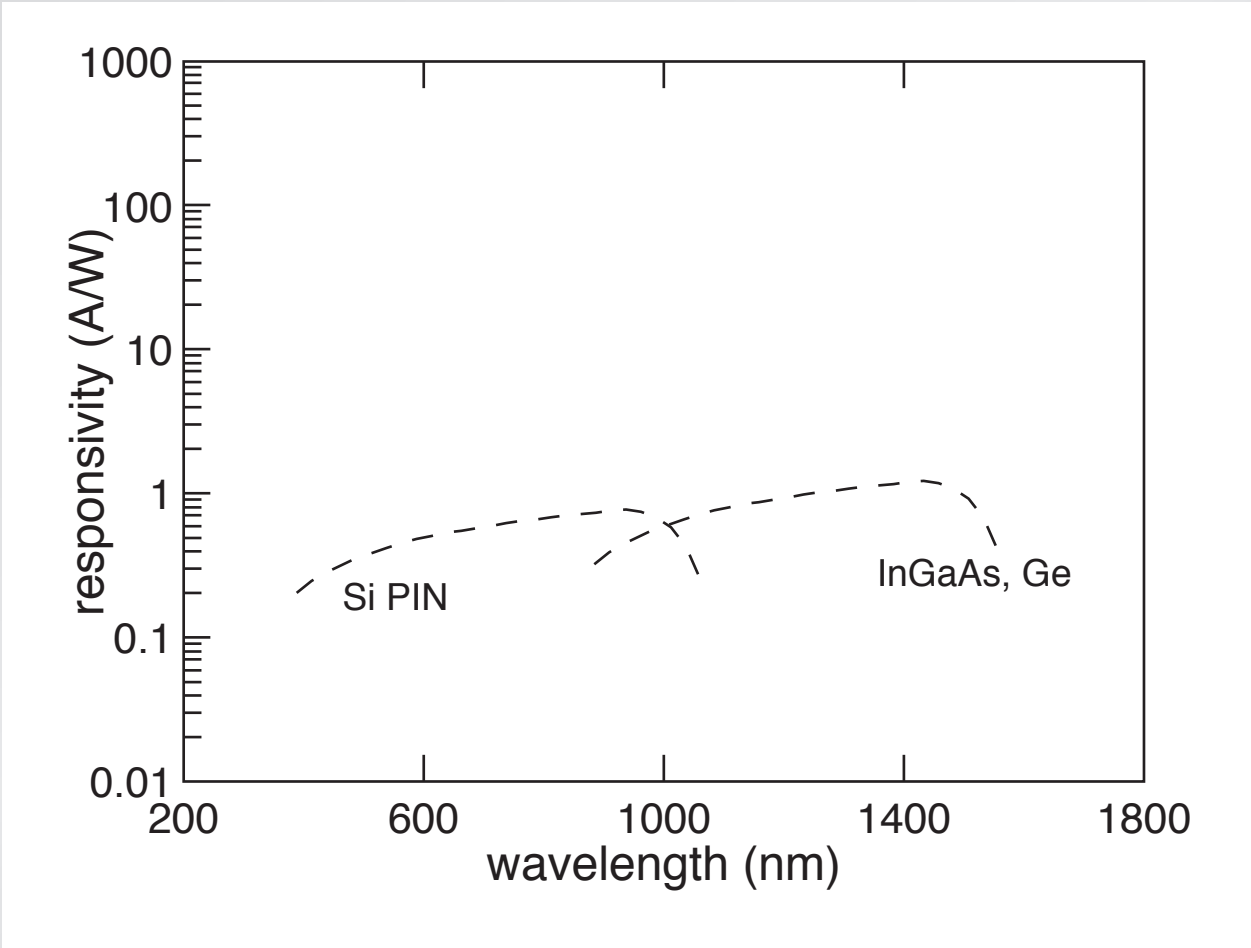
Devices

responsivity



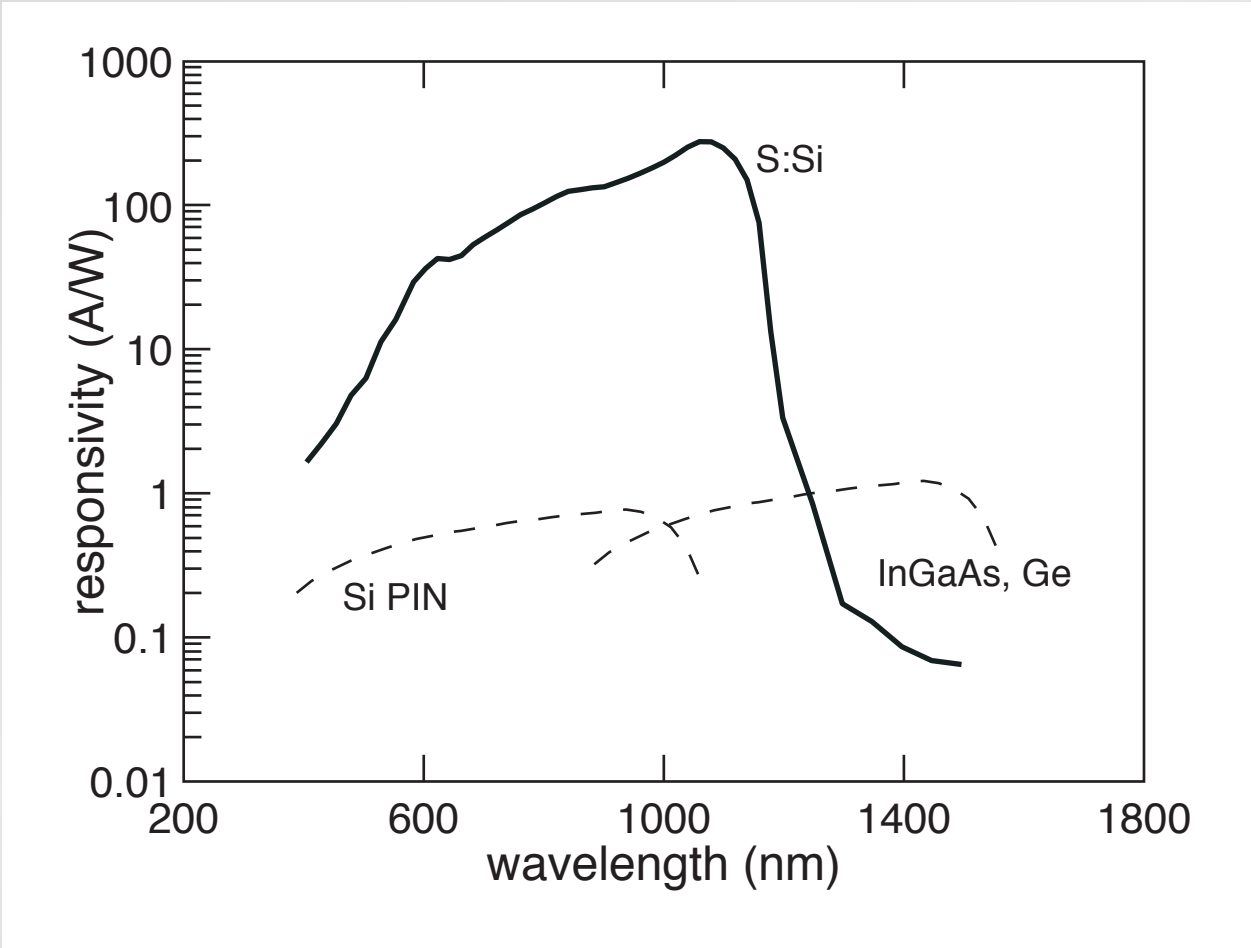
Devices

responsivity



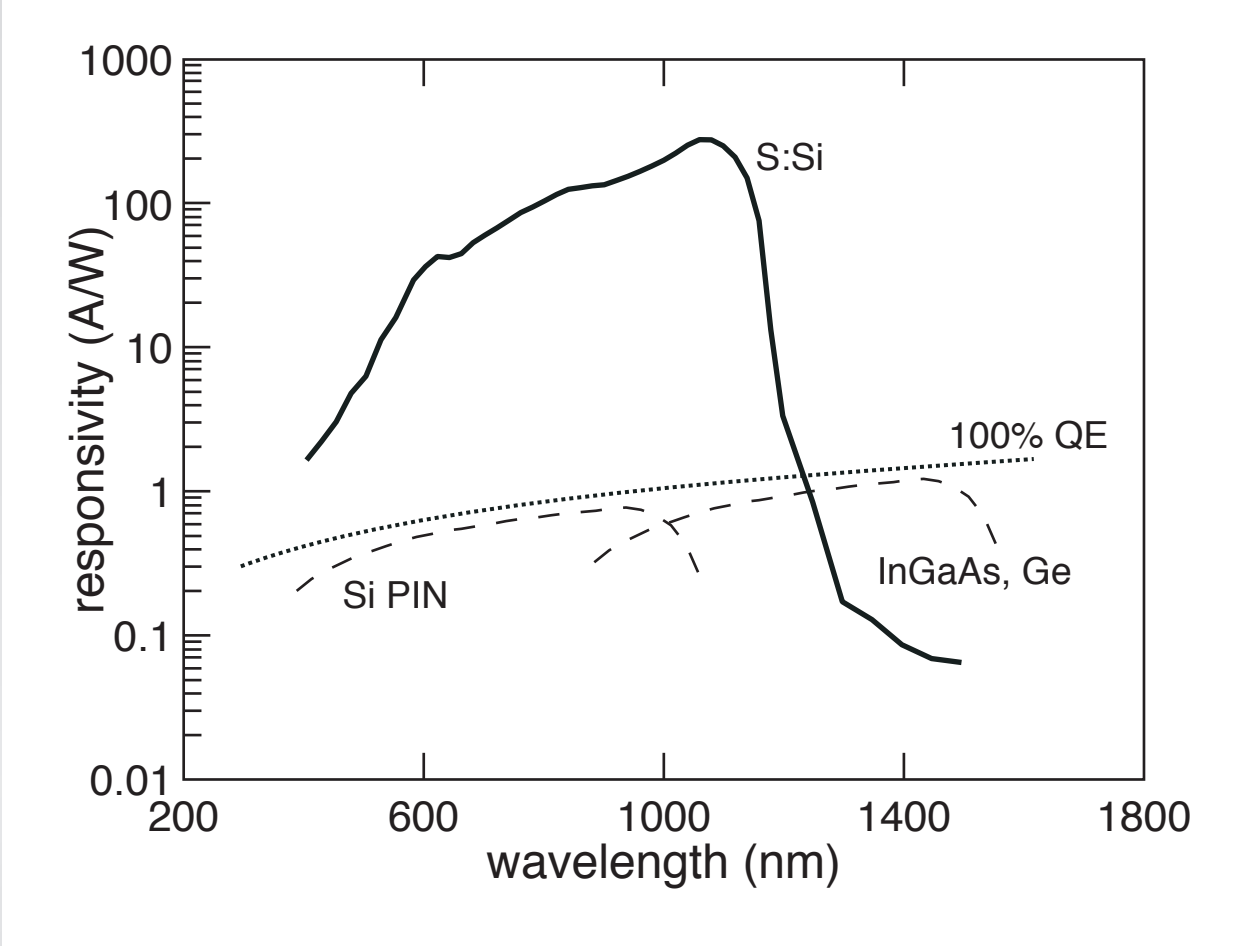
Devices

responsivity



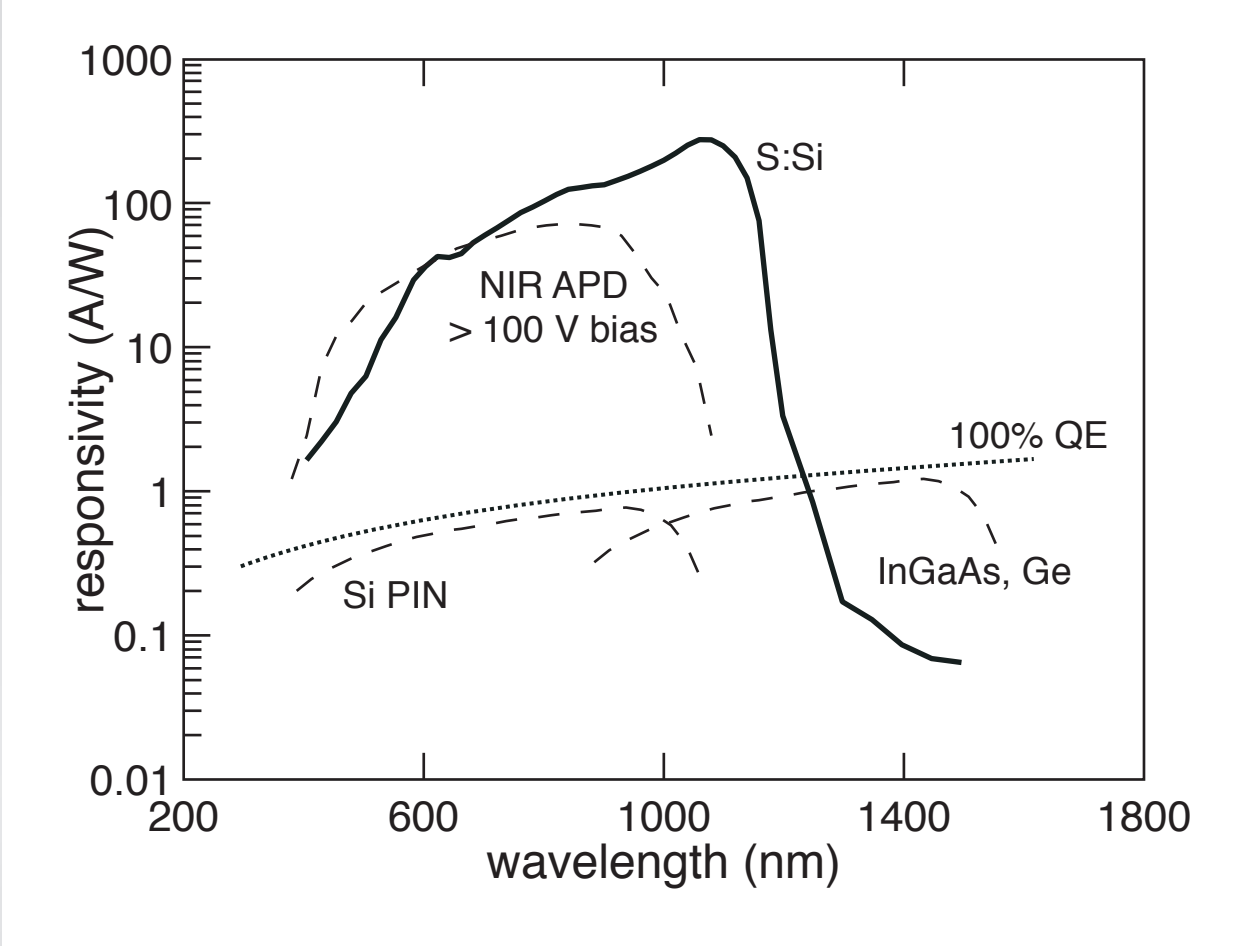
Devices

responsivity



Devices

responsivity



Devices

What causes gain?

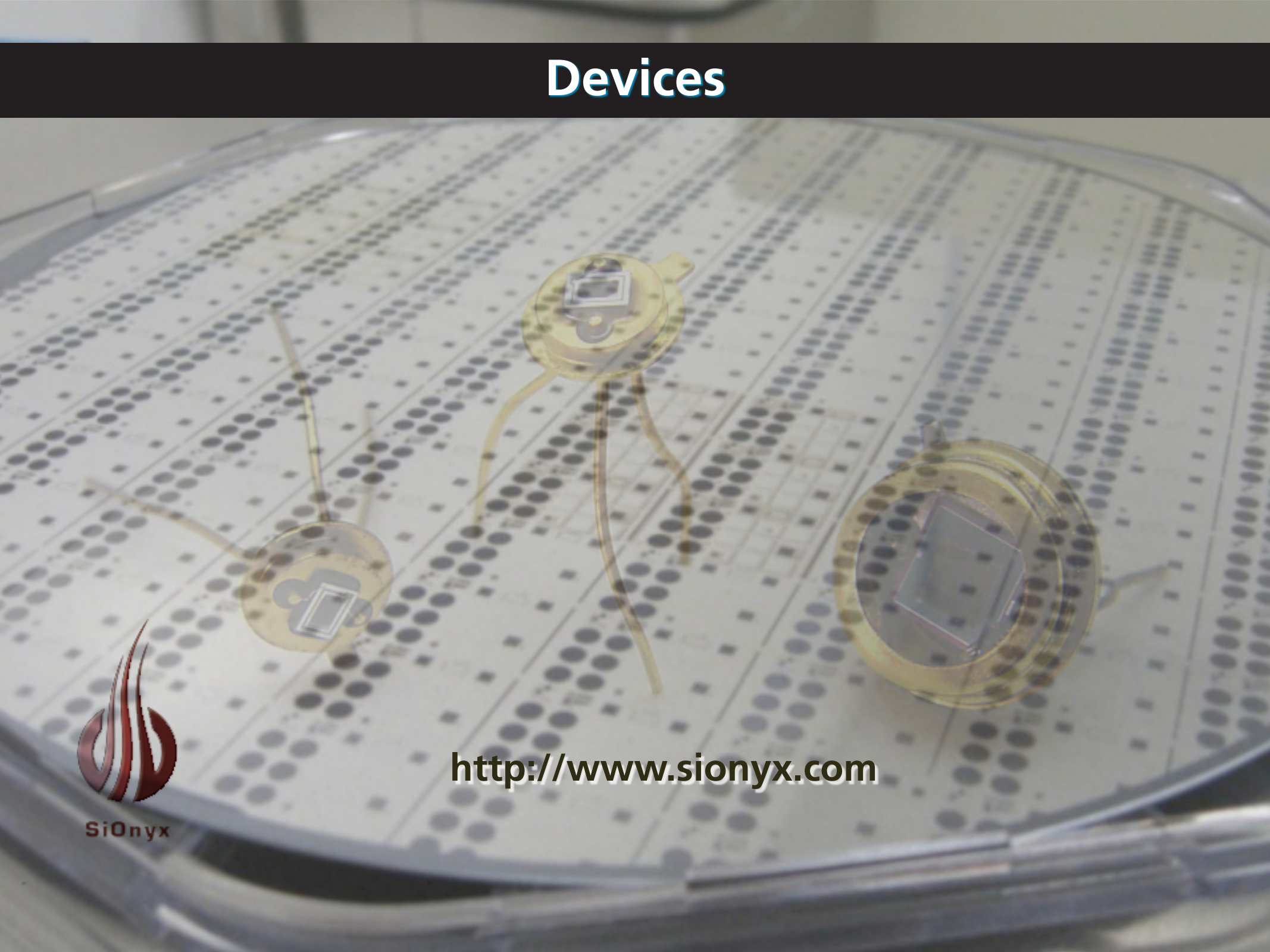
- impact excitation (avalanching)
- carrier lifetime >> transit time (photoconductive gain)
- some other mechanism

Devices

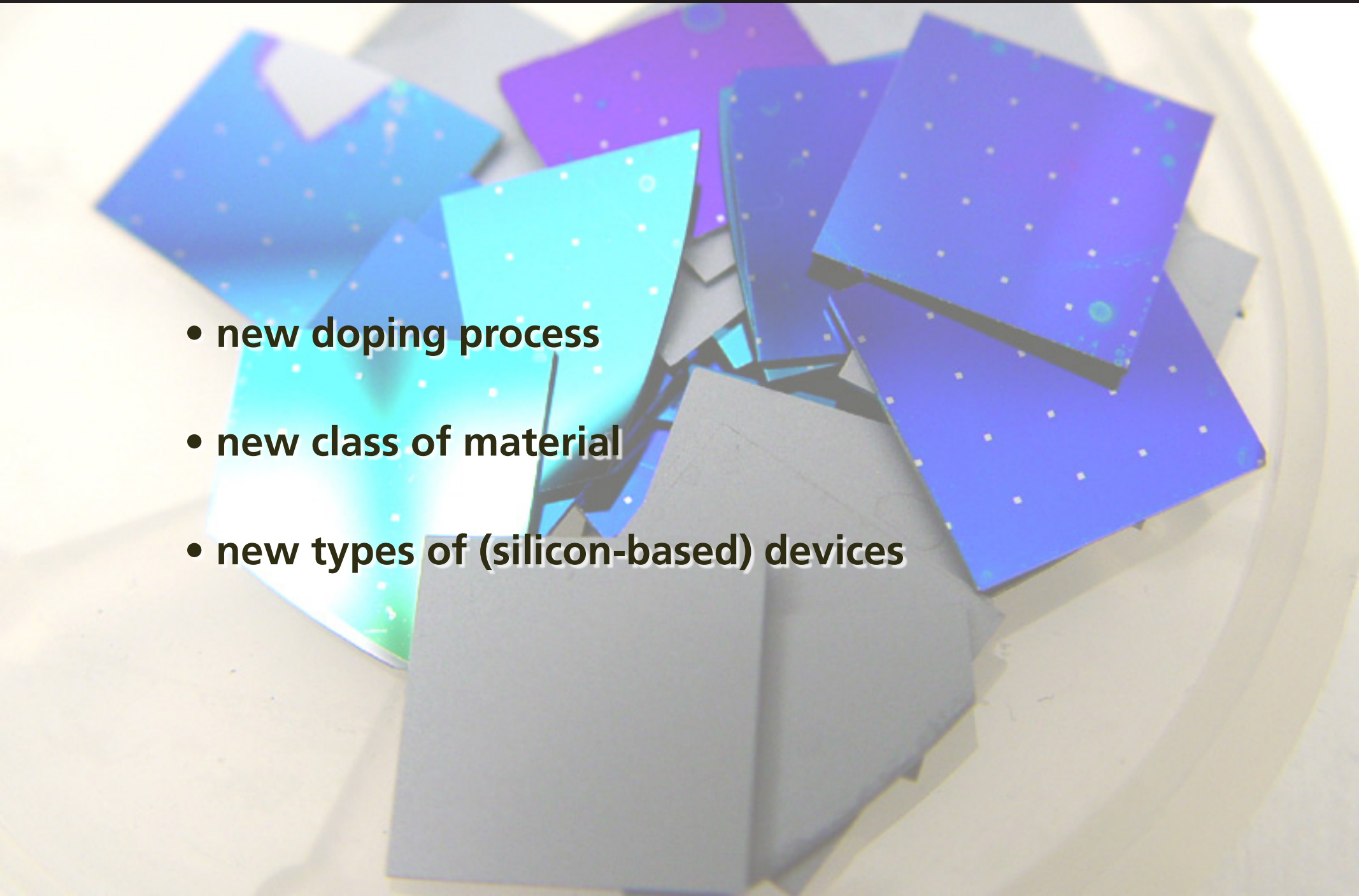
Things to keep in mind

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

Devices

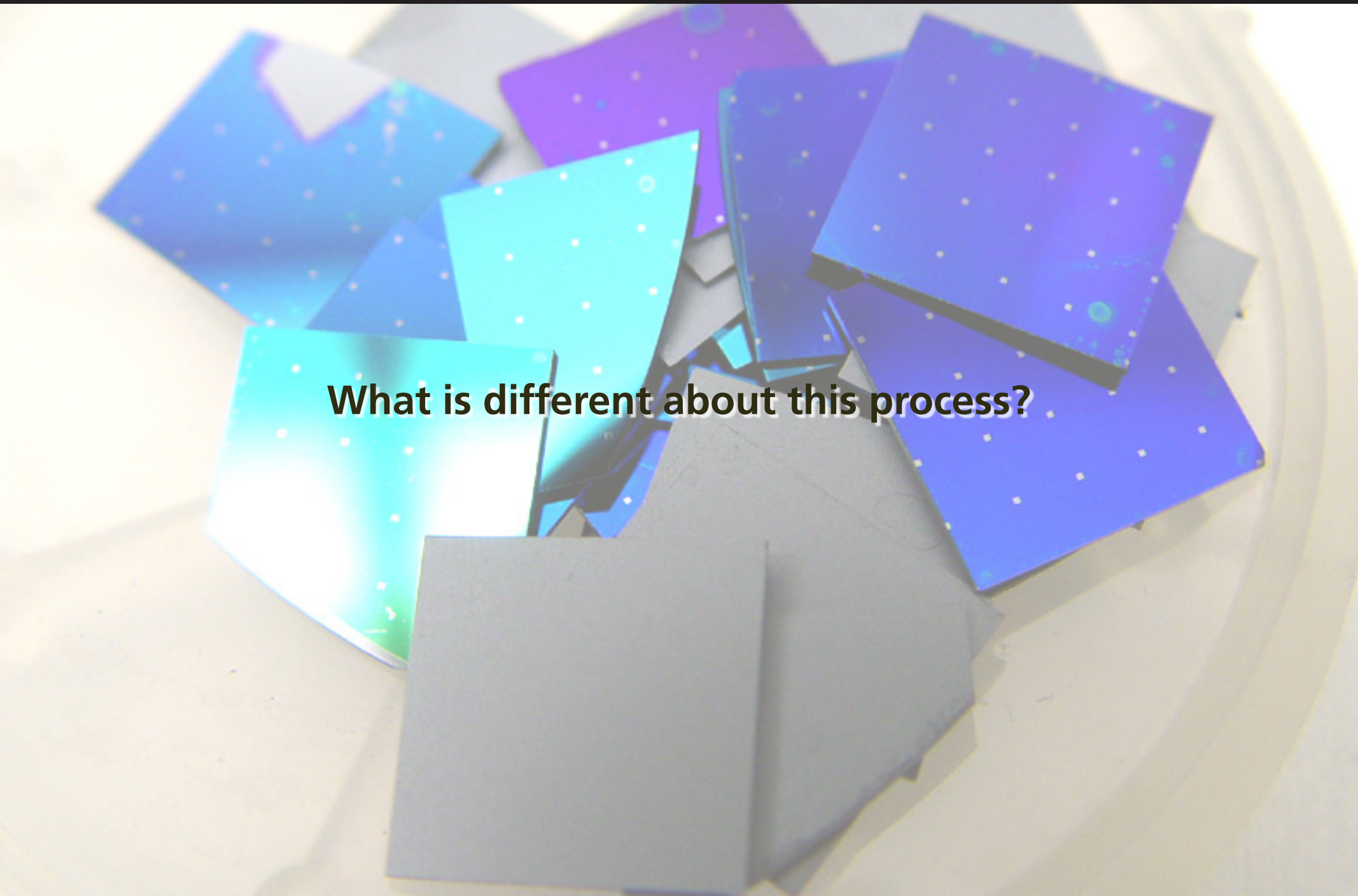


Conclusion



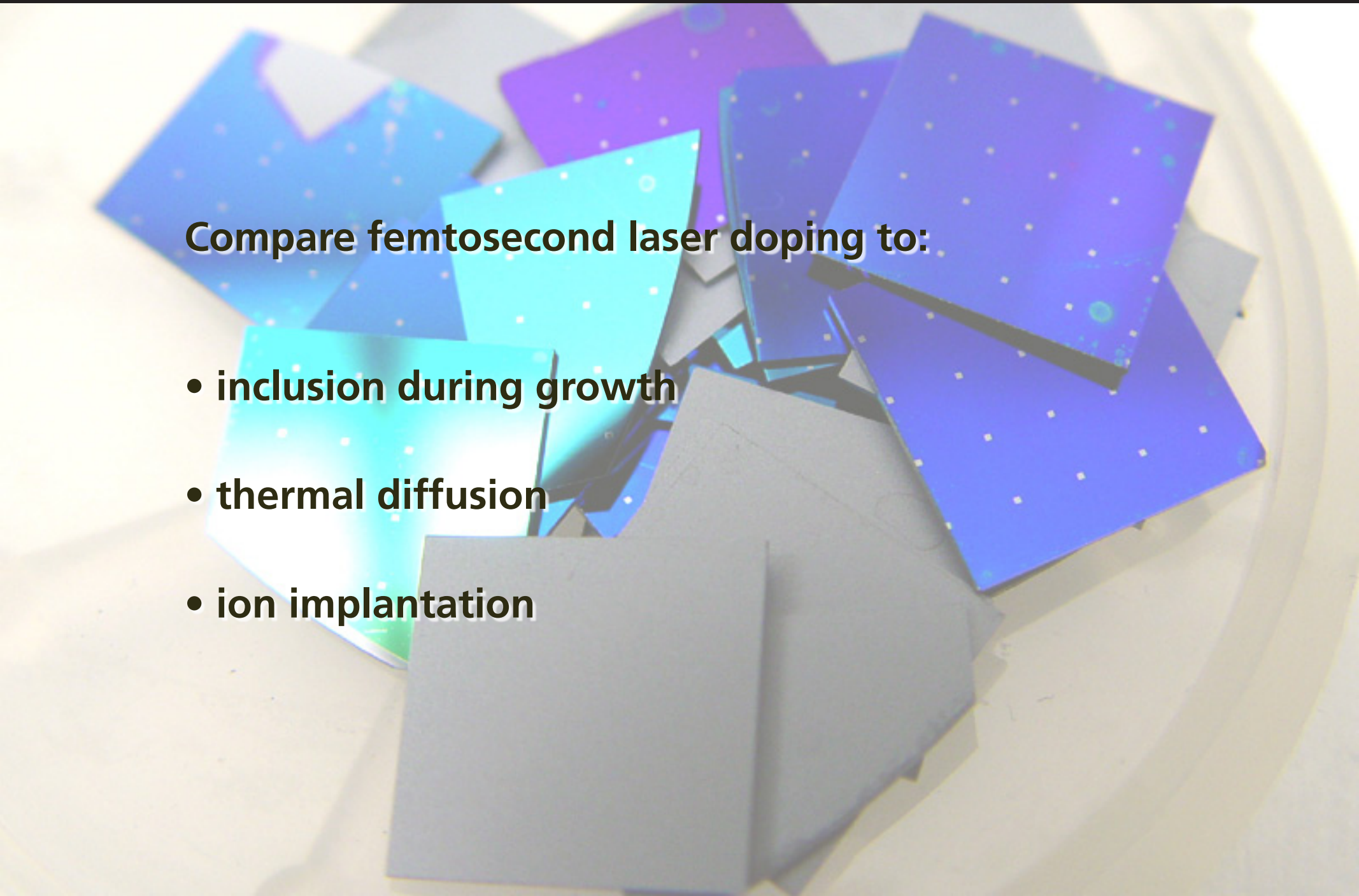
- new doping process
- new class of material
- new types of (silicon-based) devices

Conclusion



What is different about this process?

Conclusion



Compare femtosecond laser doping to:

- inclusion during growth
- thermal diffusion
- ion implantation

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Army Research Office
DARPA
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NDSEG
National Science Foundation

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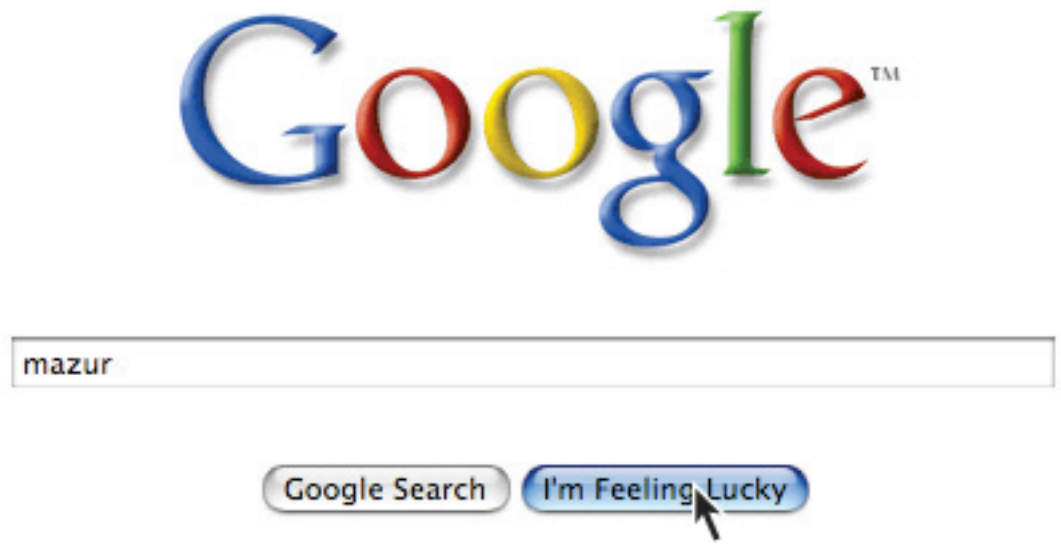
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