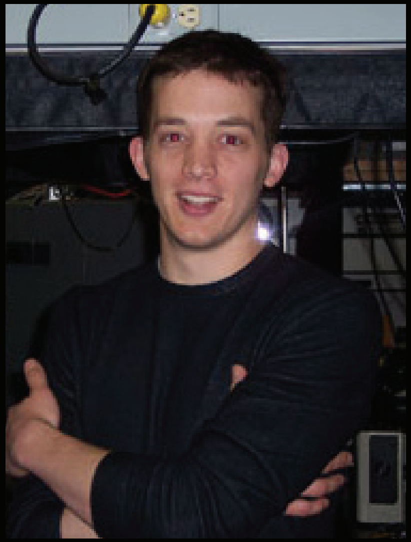
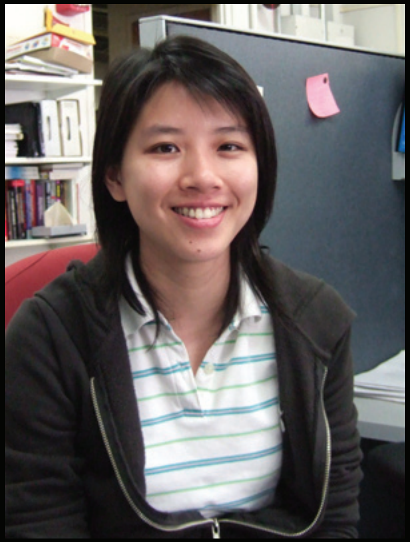
Black silicon: engineering an intermediate band in silicon for sensing and energy harvesting

Physics and Applications of "Black" Materials
DSRC/DARPA Workshop
Arlington, VA, 31 March 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)

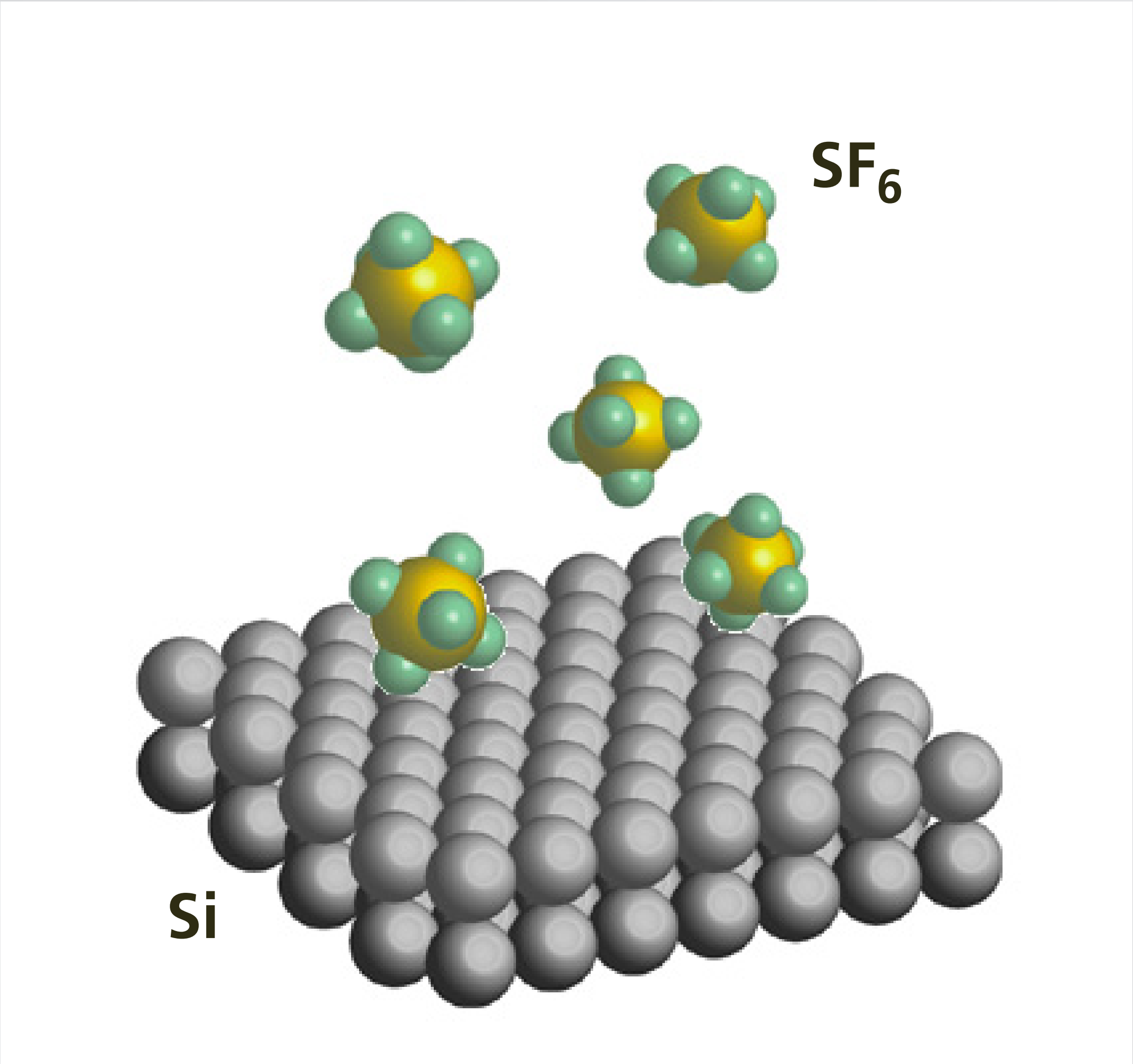
Dr. François Génin (LLNL)
Mark Wall (LLNL)

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

Dr. Pat Maloney (NVSED)

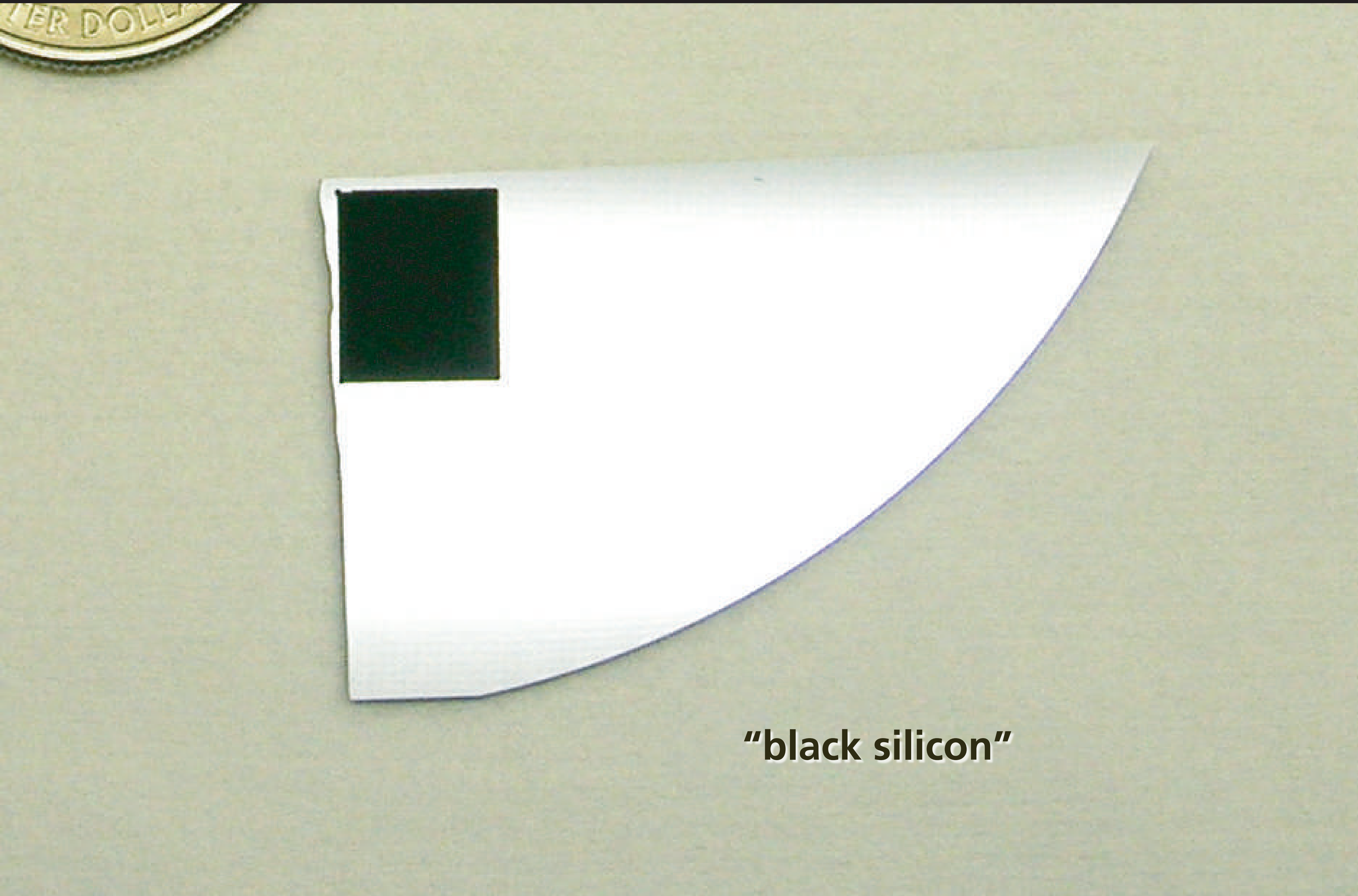
Dr. Jeffrey Warrander (ARDEC)

Introduction



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

Introduction



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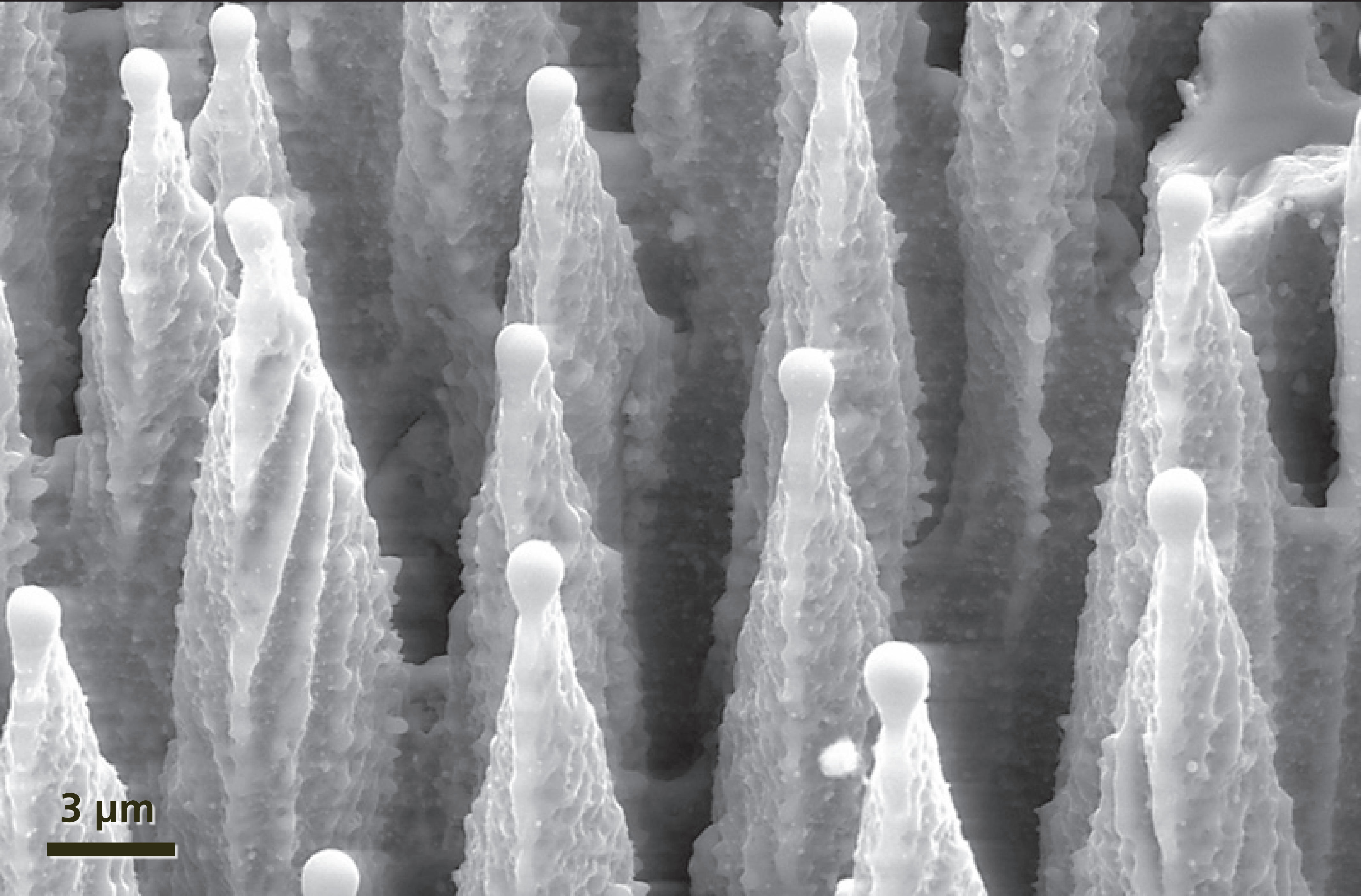

Introduction

Since first publication (1998):

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- **optoelectronic properties (2001)**

Introduction

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- optoelectronic properties (2001)
- field emission (2001)

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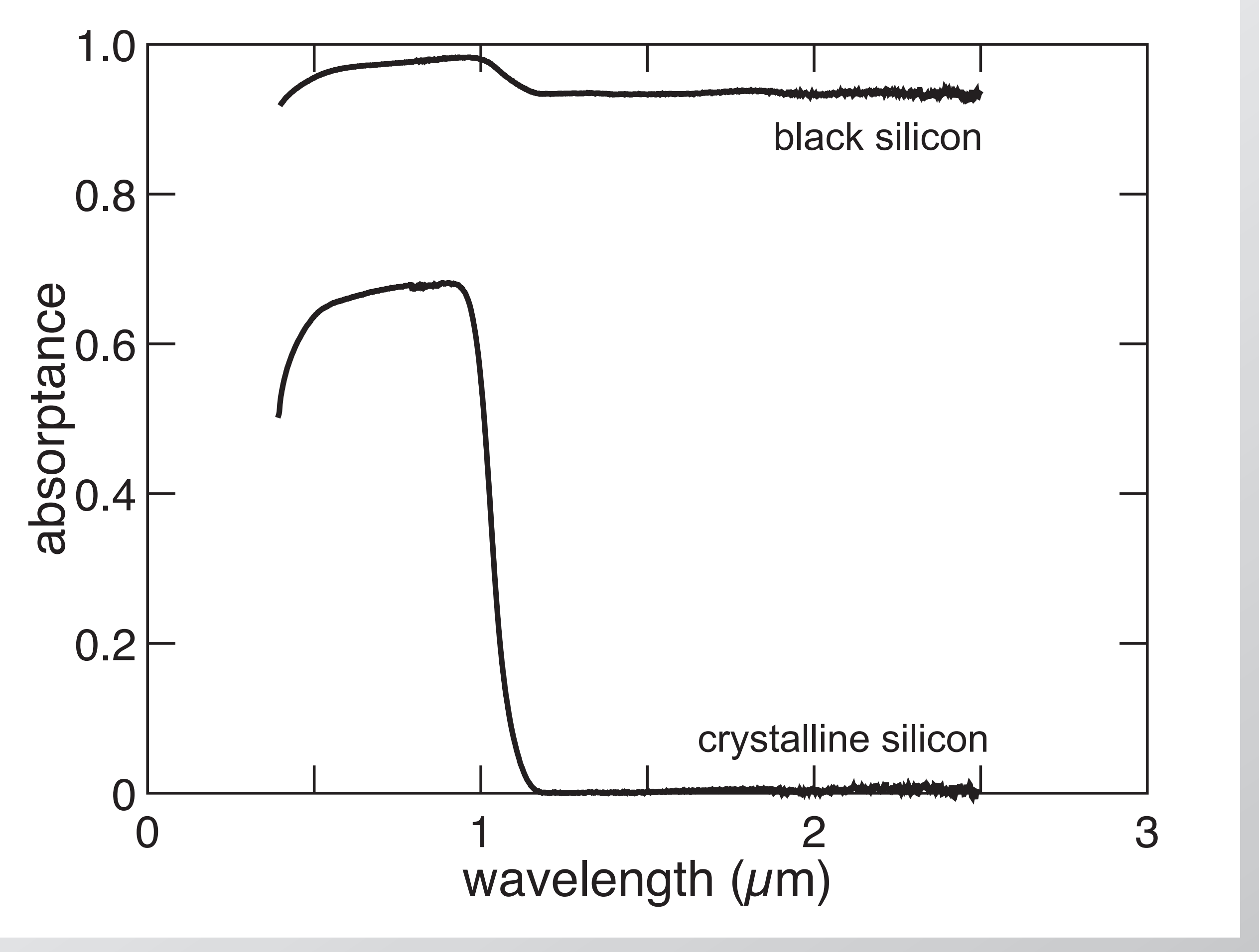
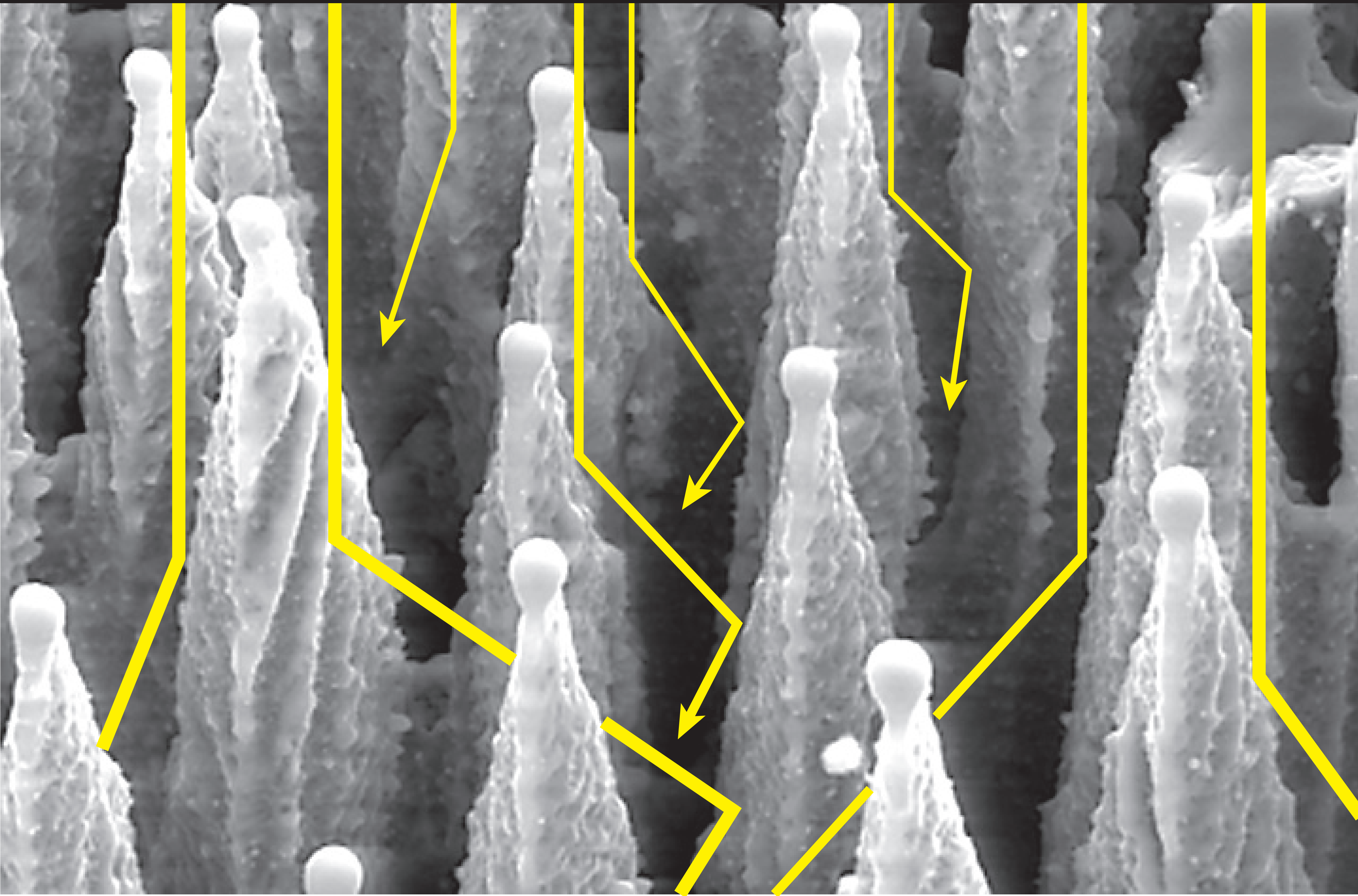
6 Ph.D. Theses and 12 patents

Introduction

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



Introduction



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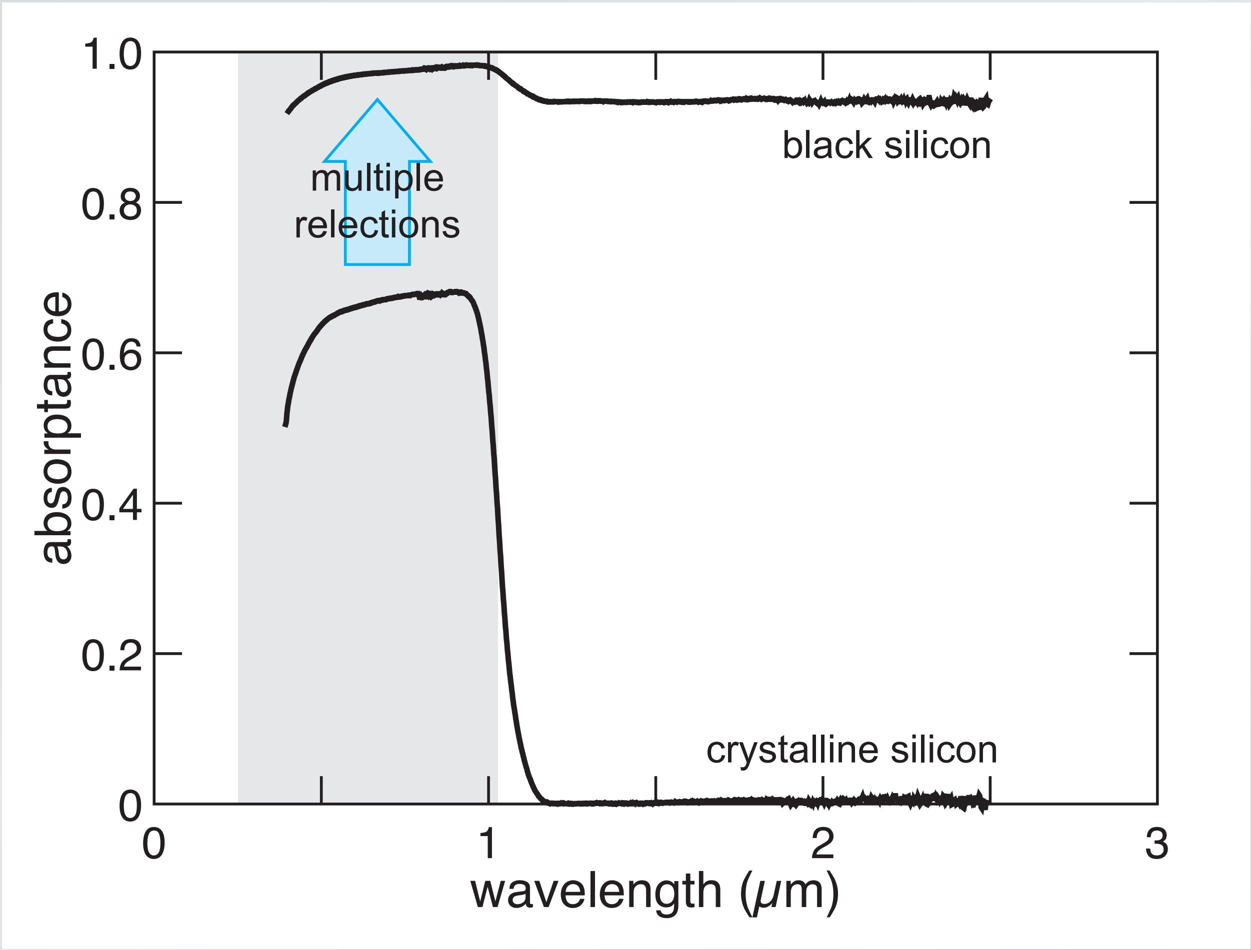

Introduction

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
		SIMS
responsivity		RBS
photoconductivity		ion channeling

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a decade of research

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responsivity
photoconductivity

gap
impurity band
transitions

Introduction

a decade of research

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

responsivity
photoconductivity

gap impurity band transitions	carrier concentration mobilities junction properties	

Introduction

a decade of research

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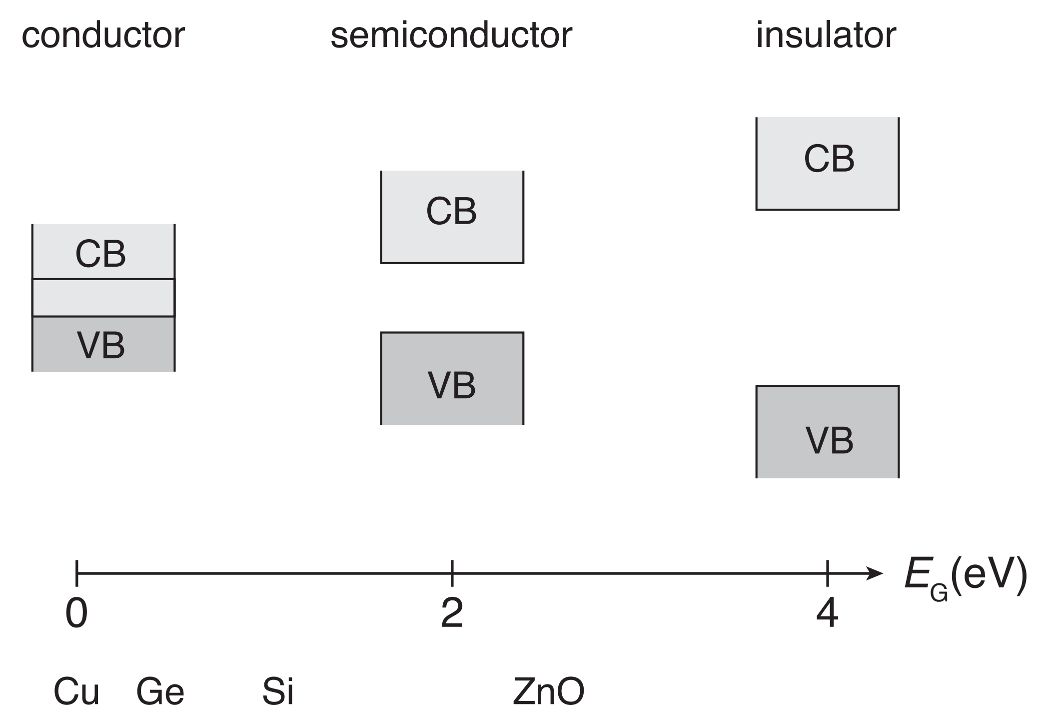
responsivity		RBS
photoconductivity		ion channeling
gap	carrier concentration	morphology
impurity band	mobilities	composition
transitions	junction properties	atomic structure

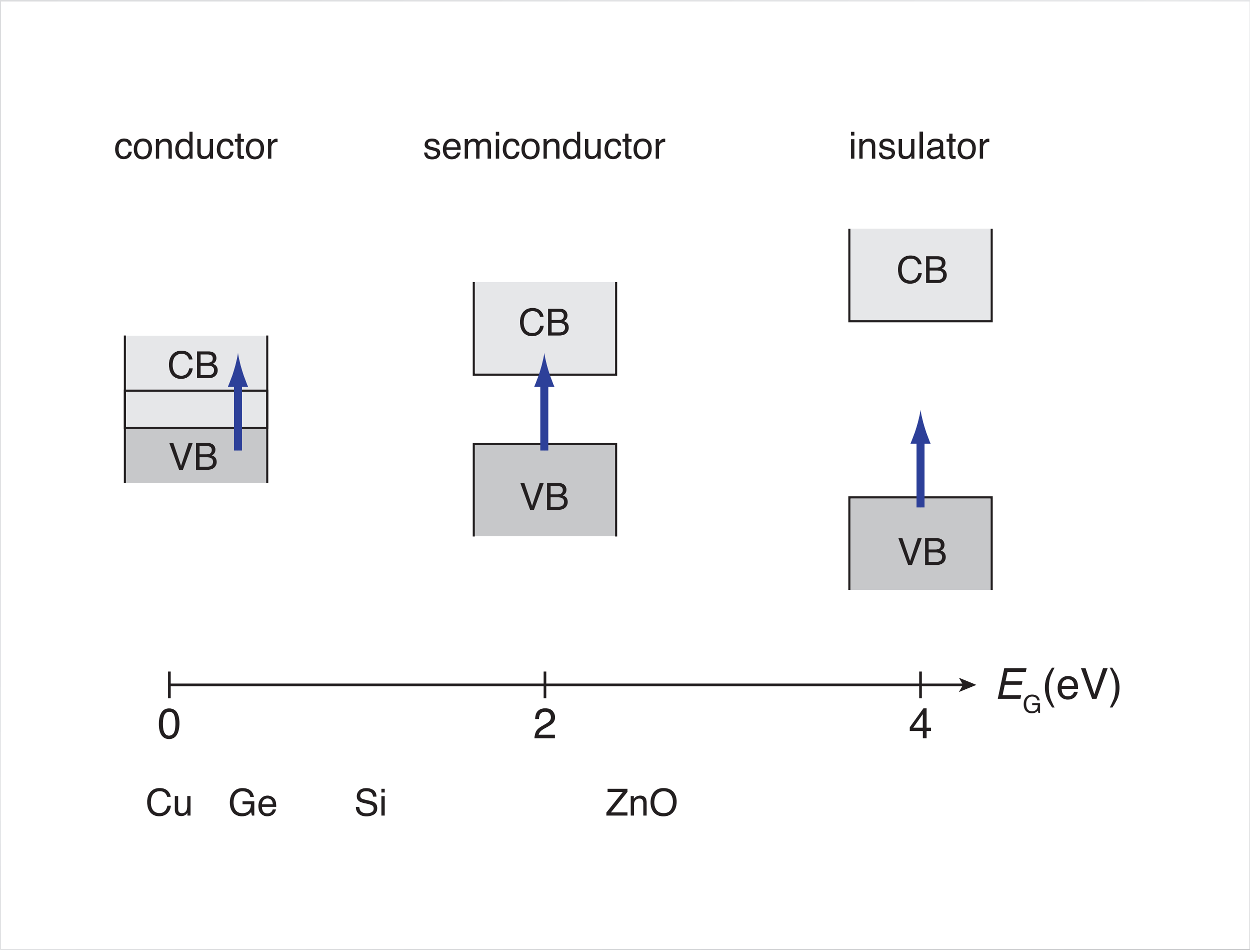
Introduction

new process & new class of material!



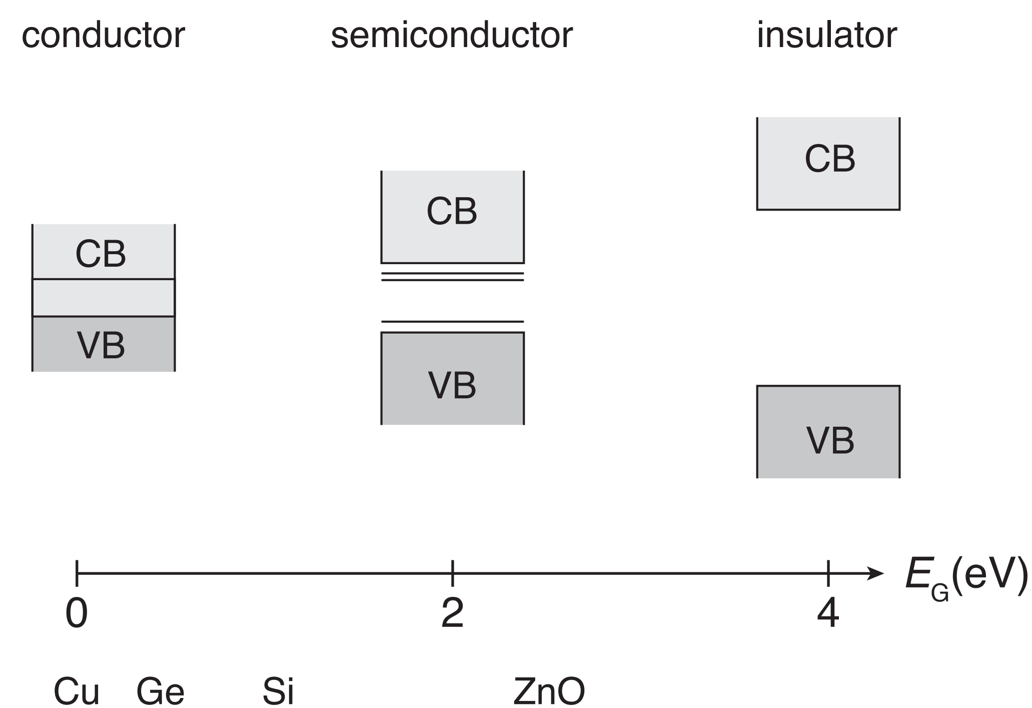
Introduction

gap determines optical and electronic properties



Introduction

shallow-level dopants control electronic properties



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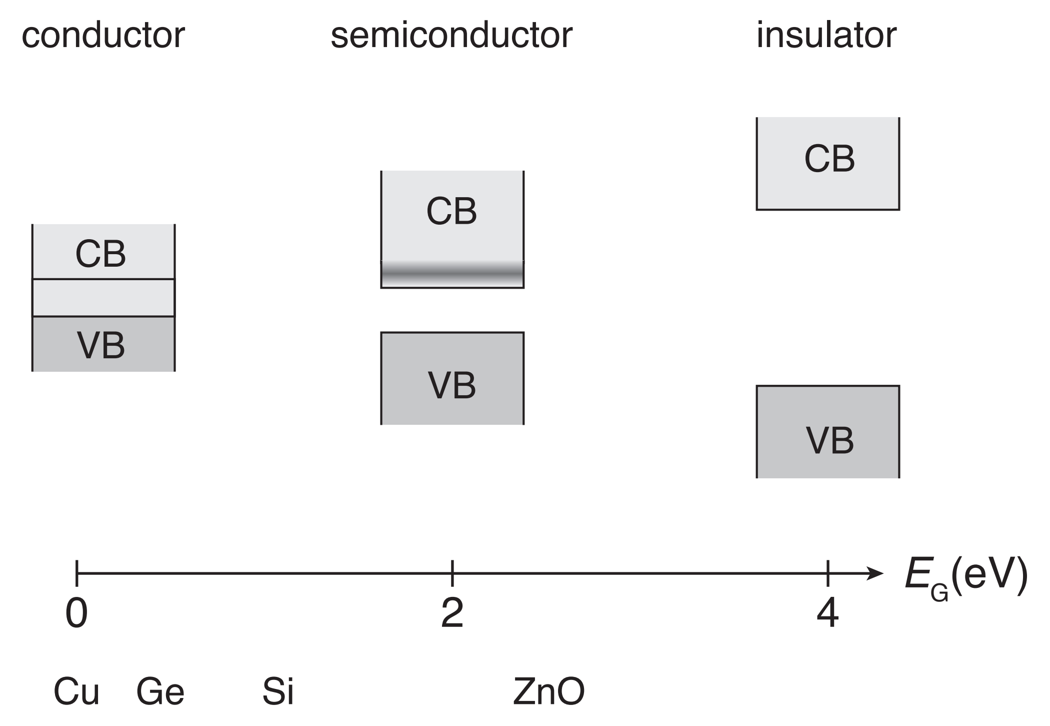
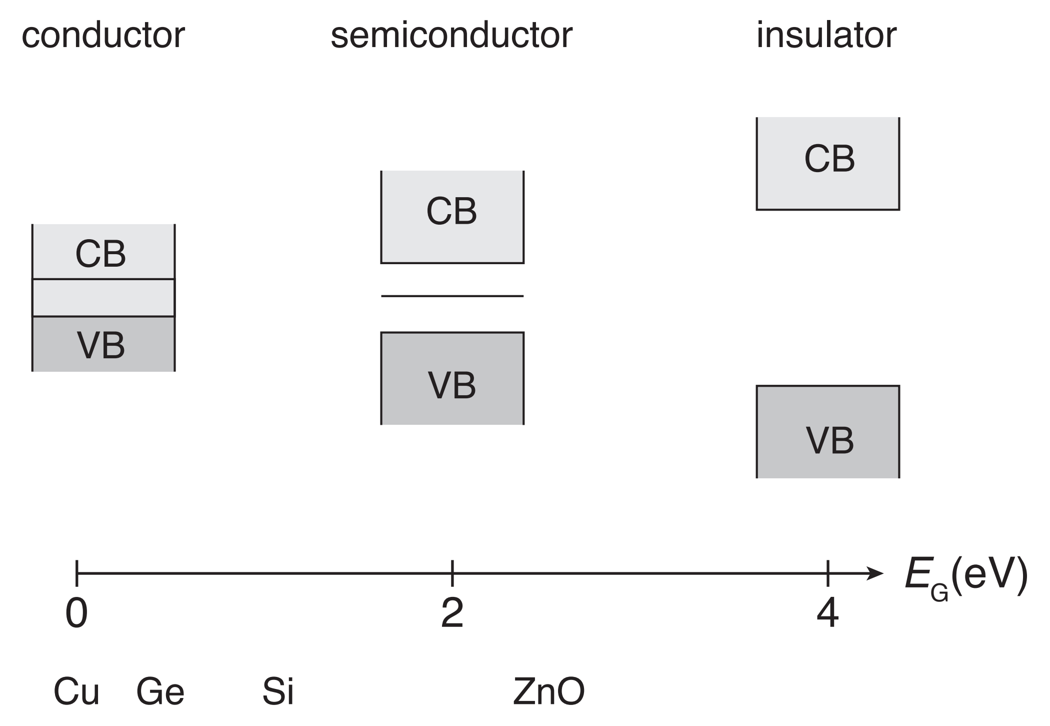


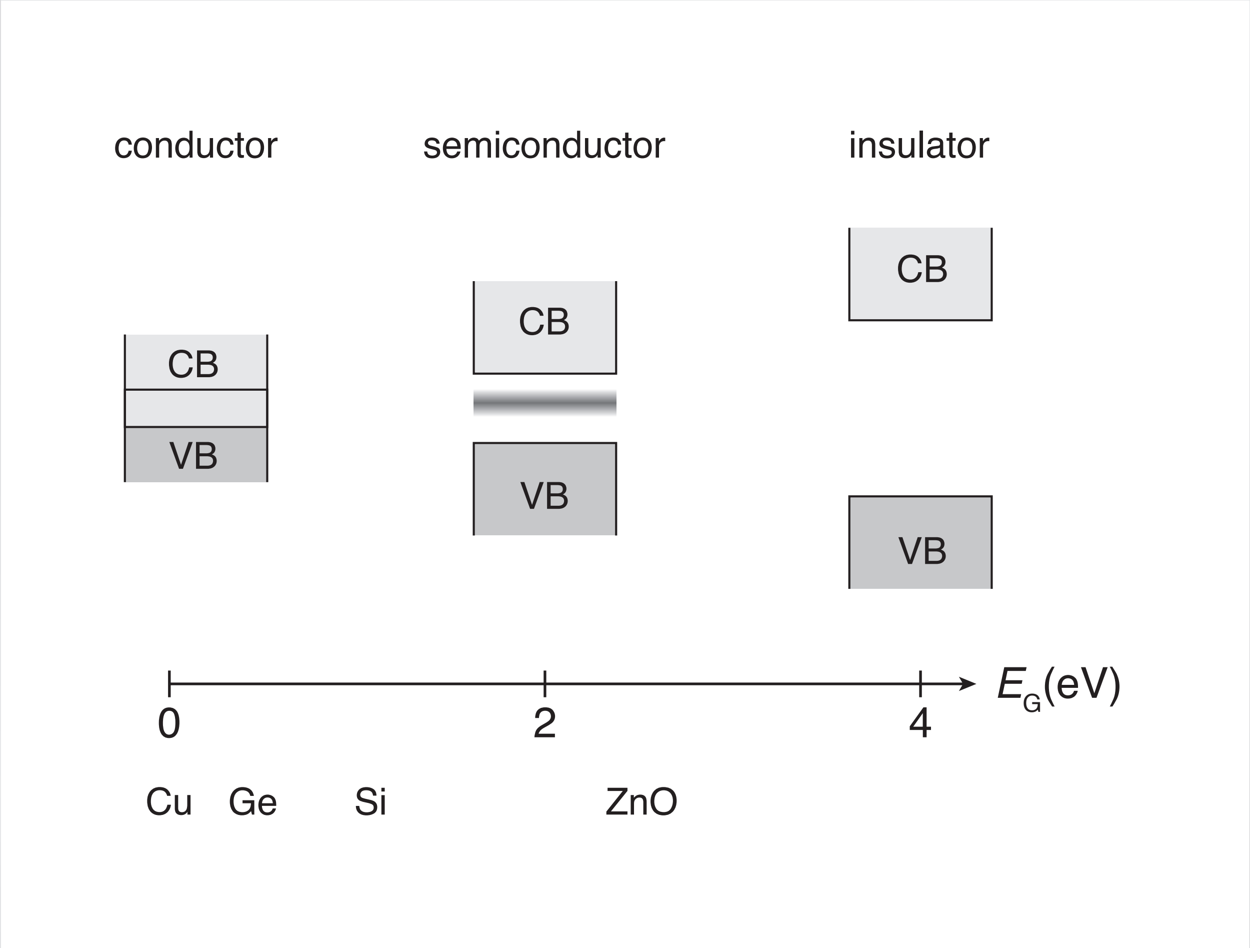
Introduction

deep-level dopants typically avoided



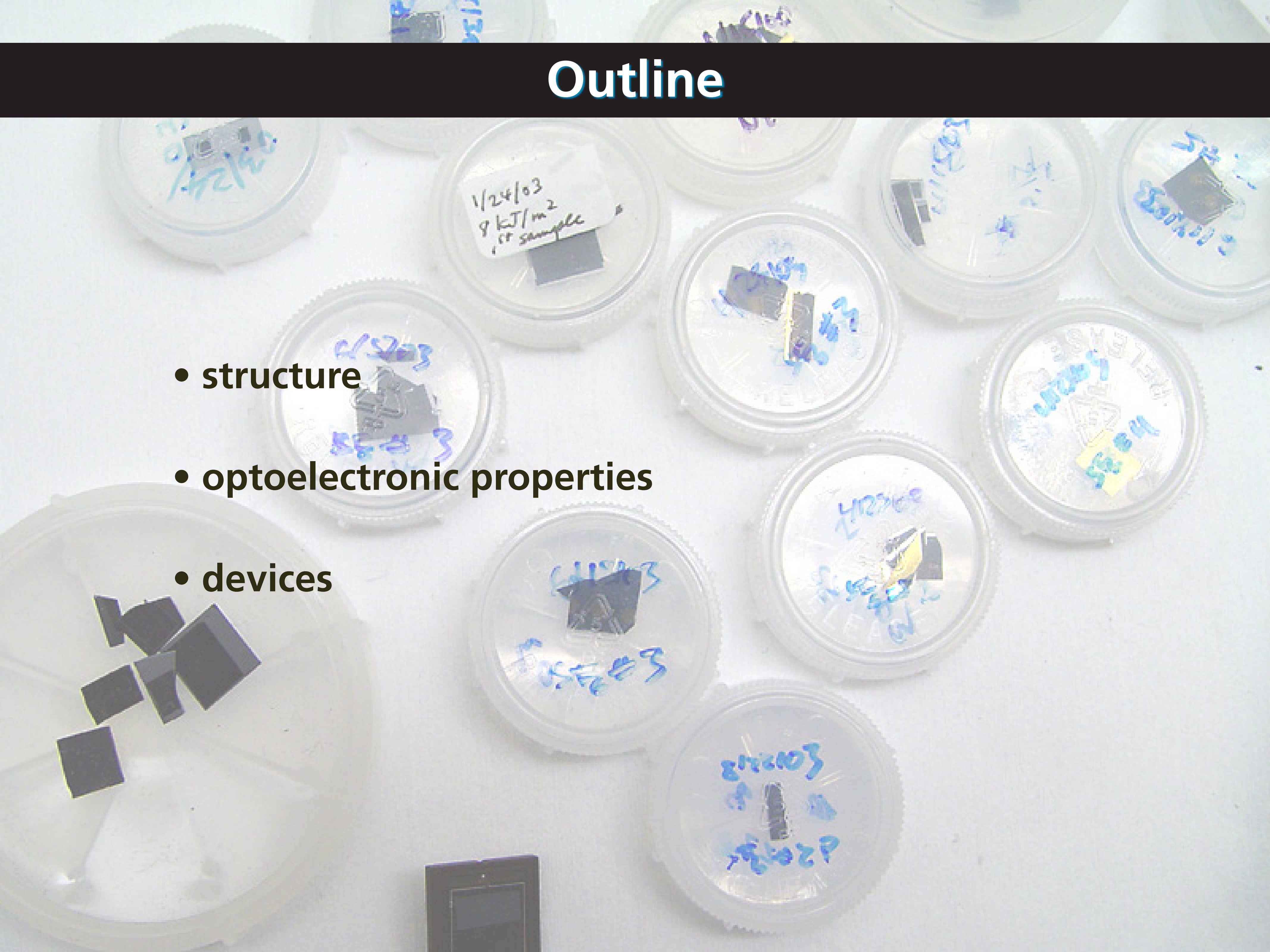
Introduction

femtosecond laser-doping gives rise to intermediate band

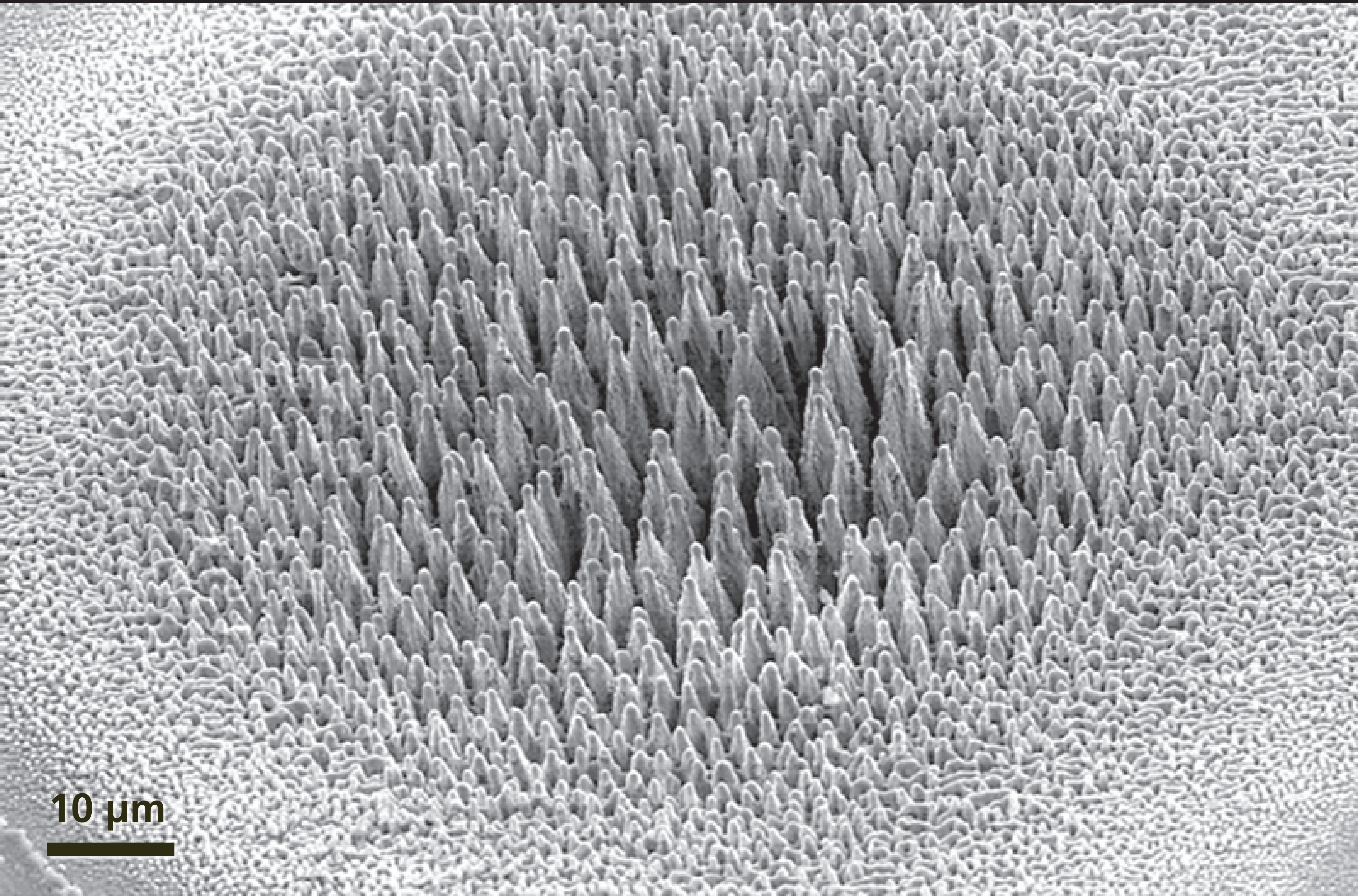


Outline

- structure
- optoelectronic properties
- devices



Structure



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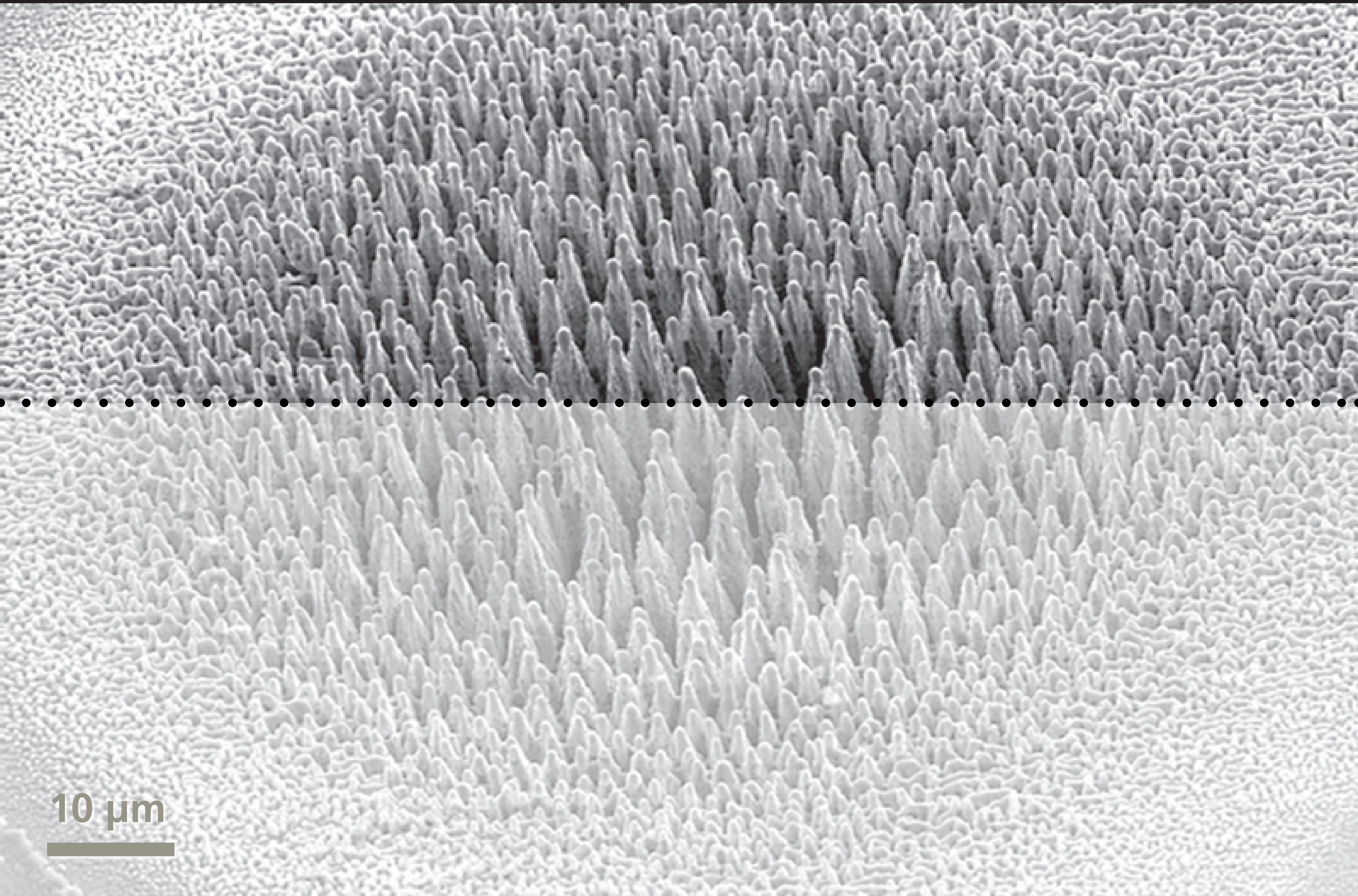

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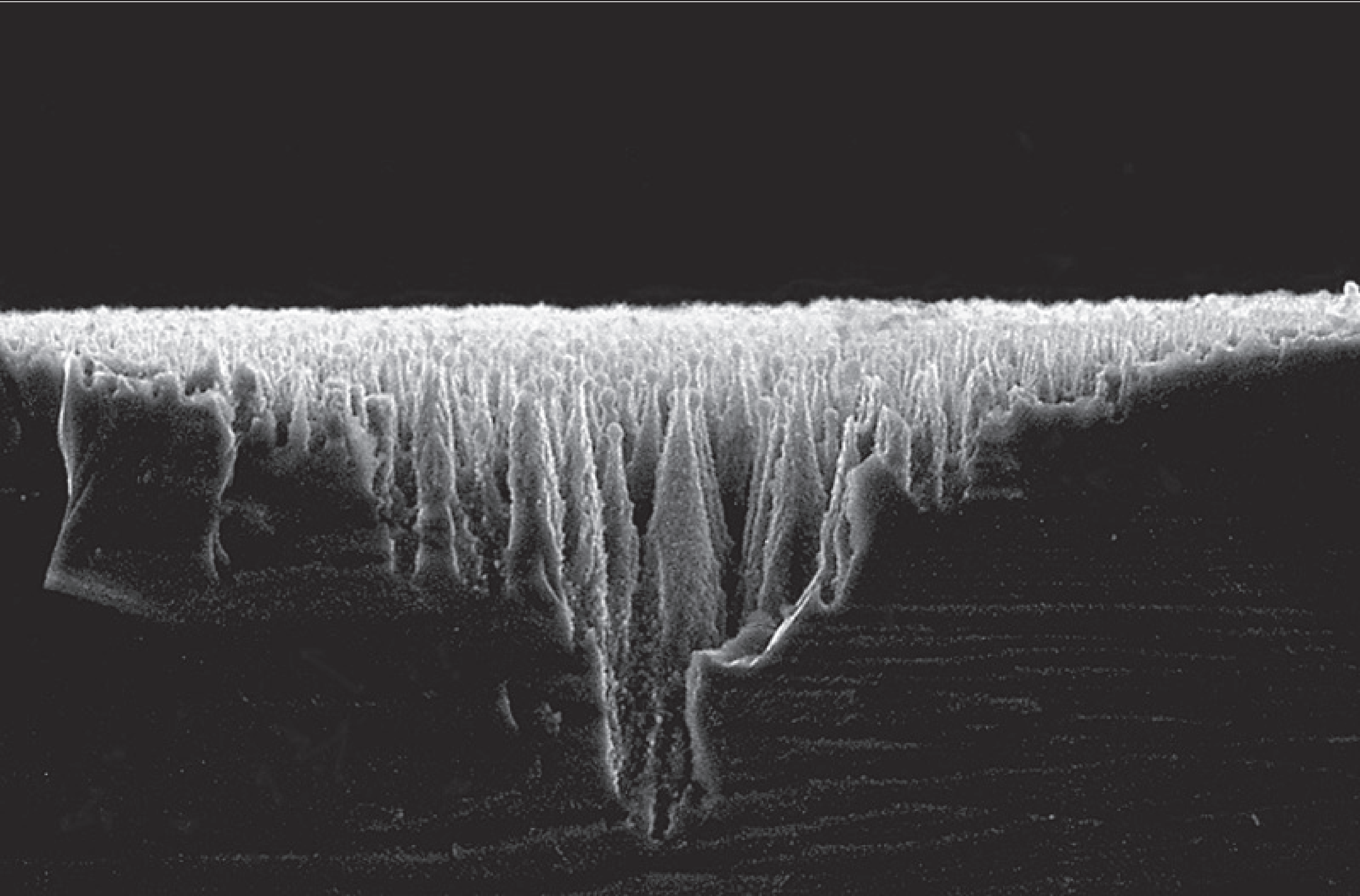

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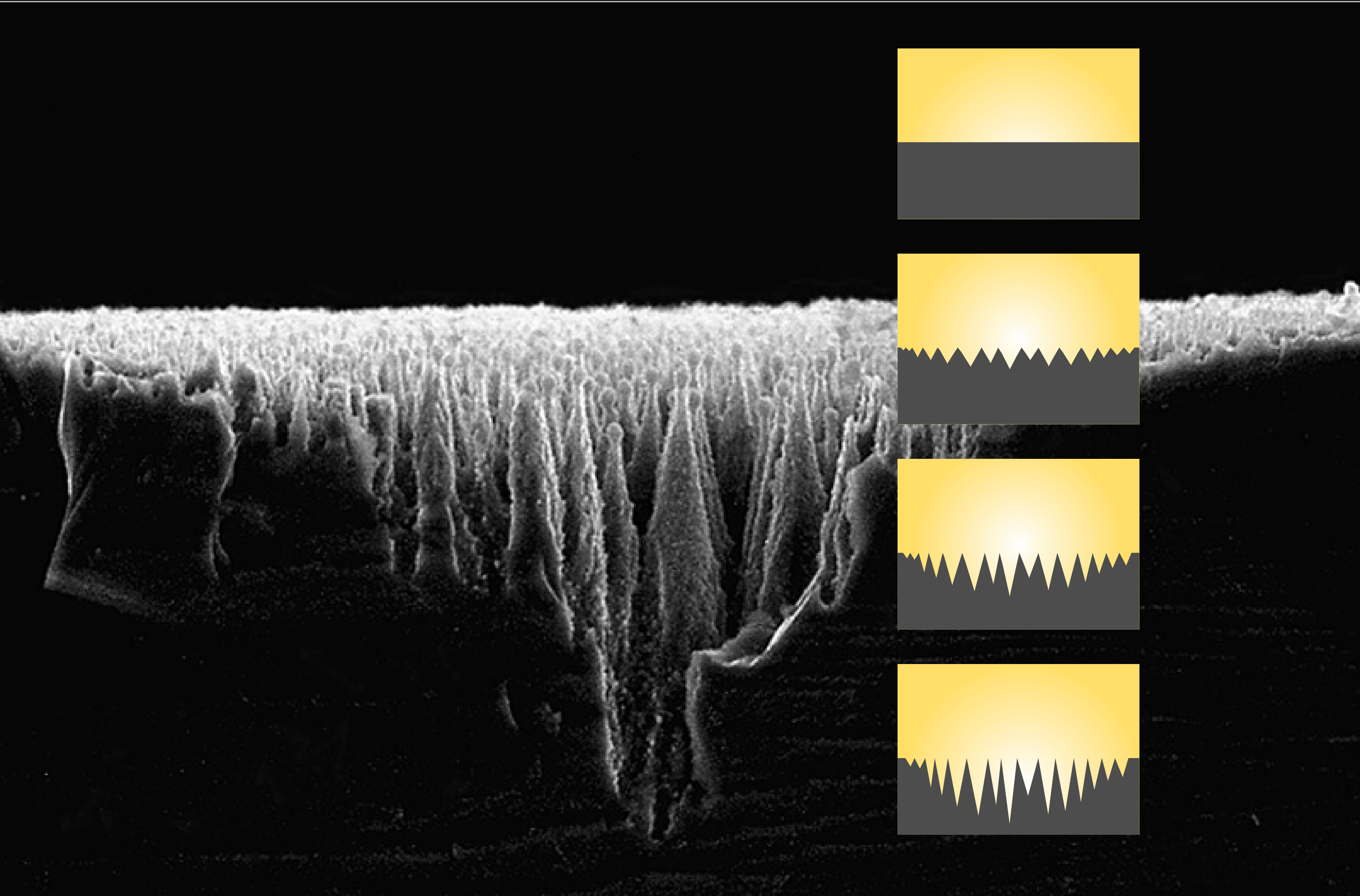
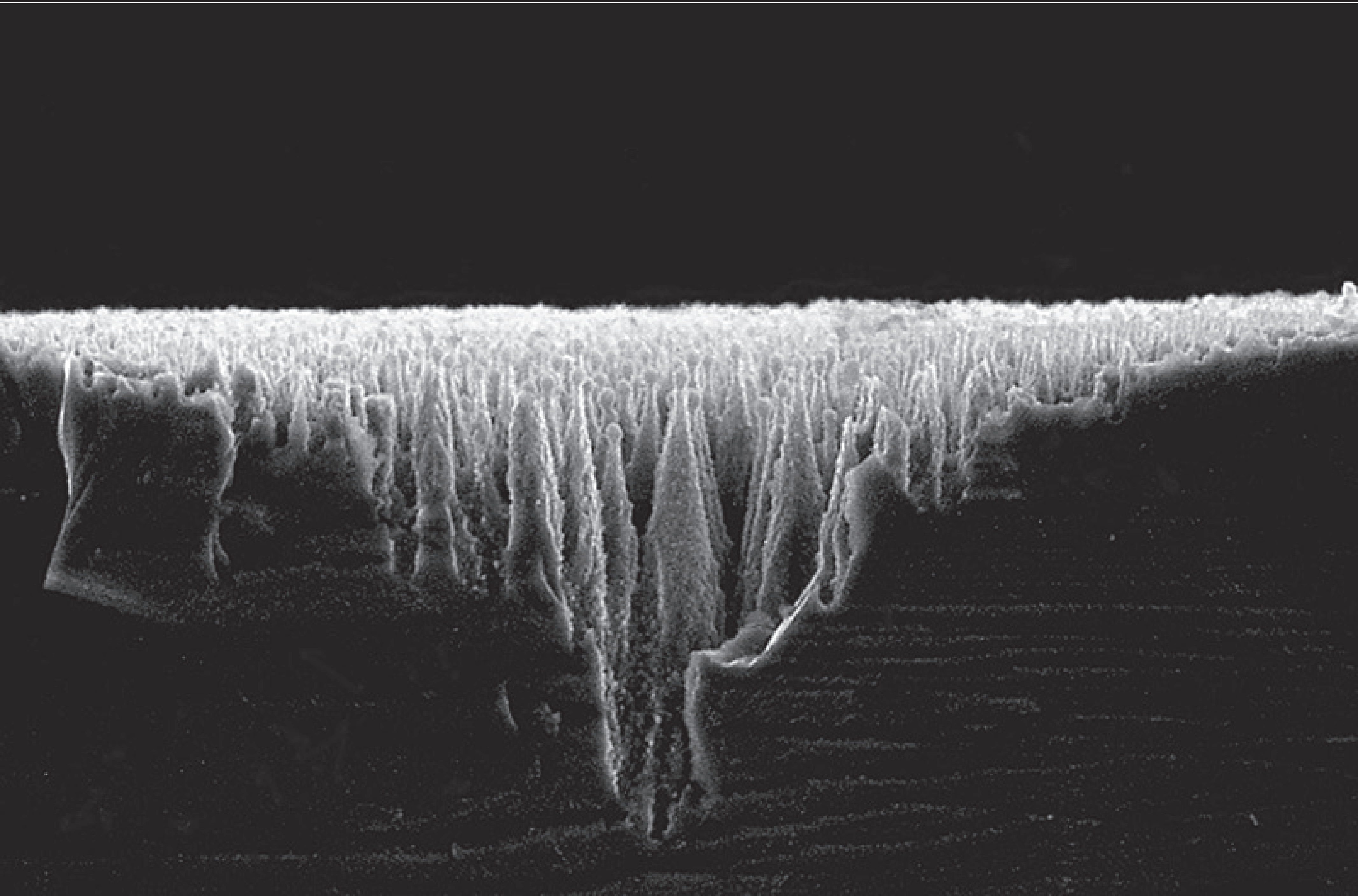


Structure



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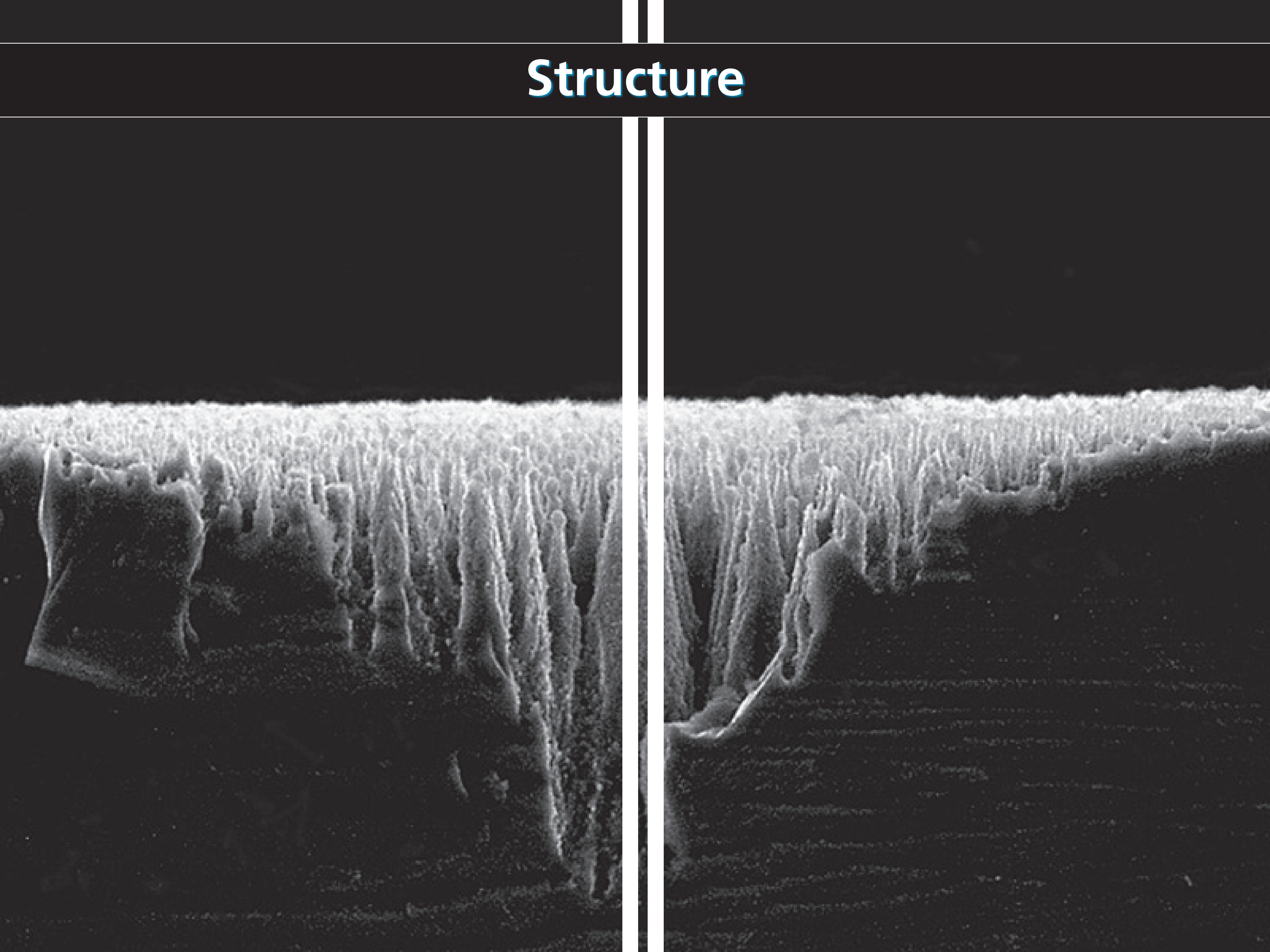
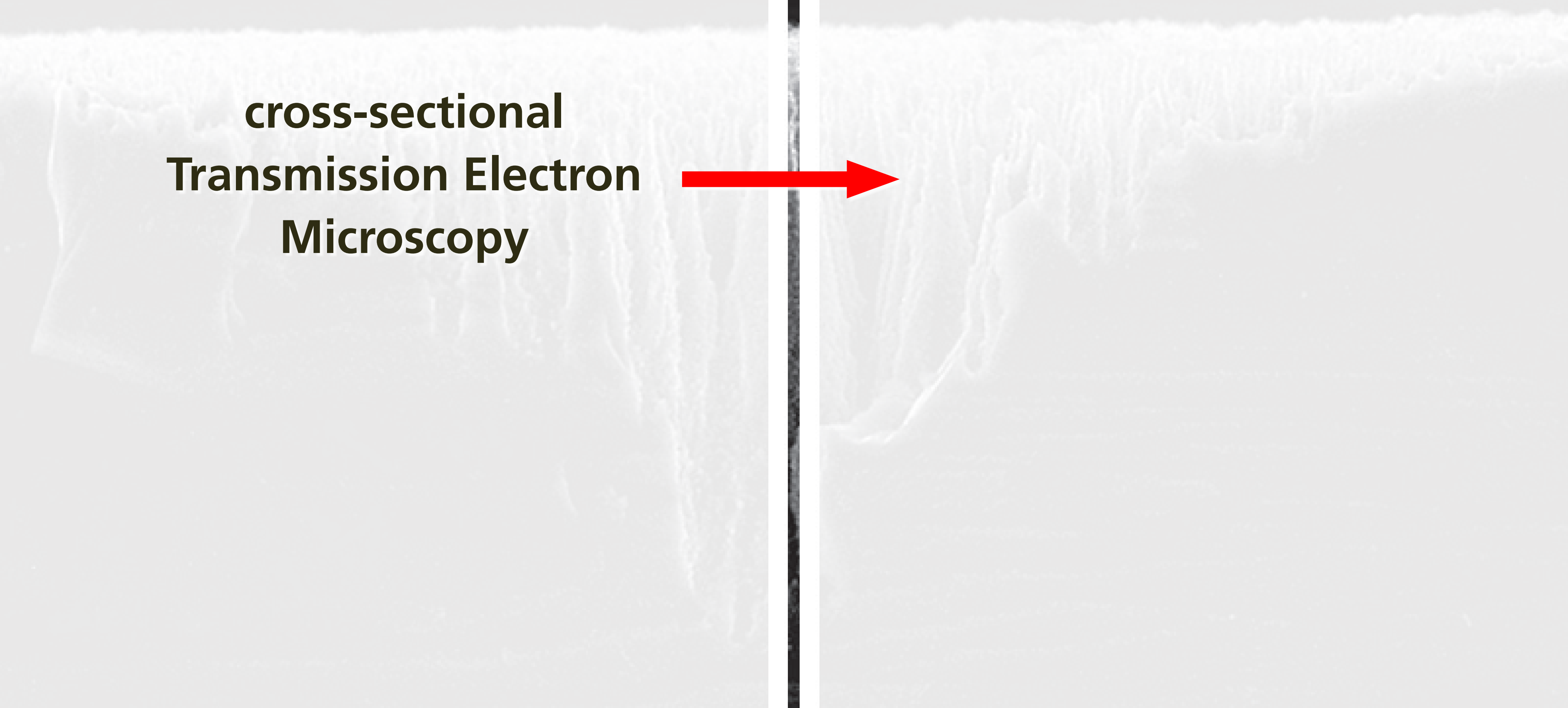
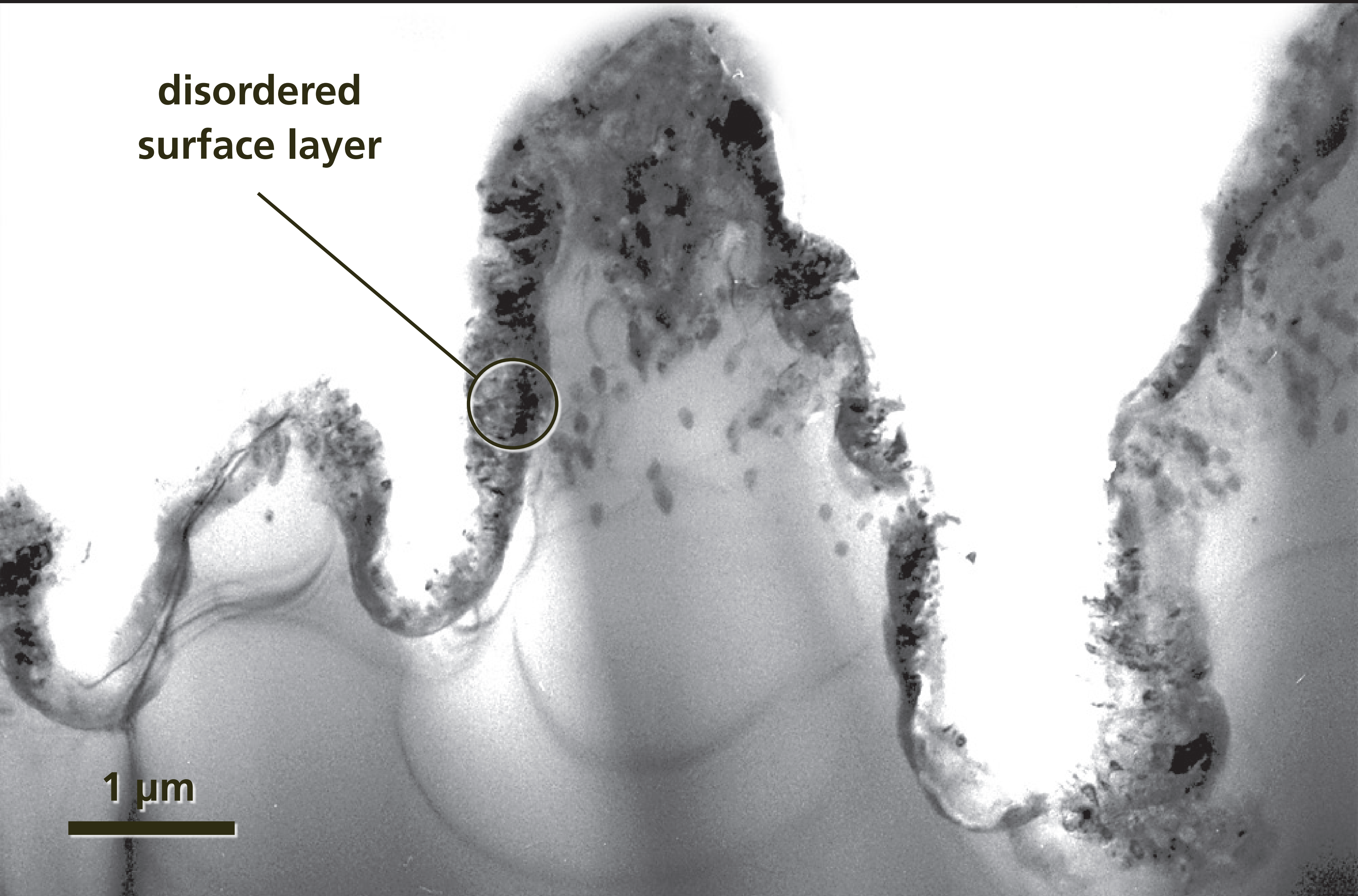


Structure

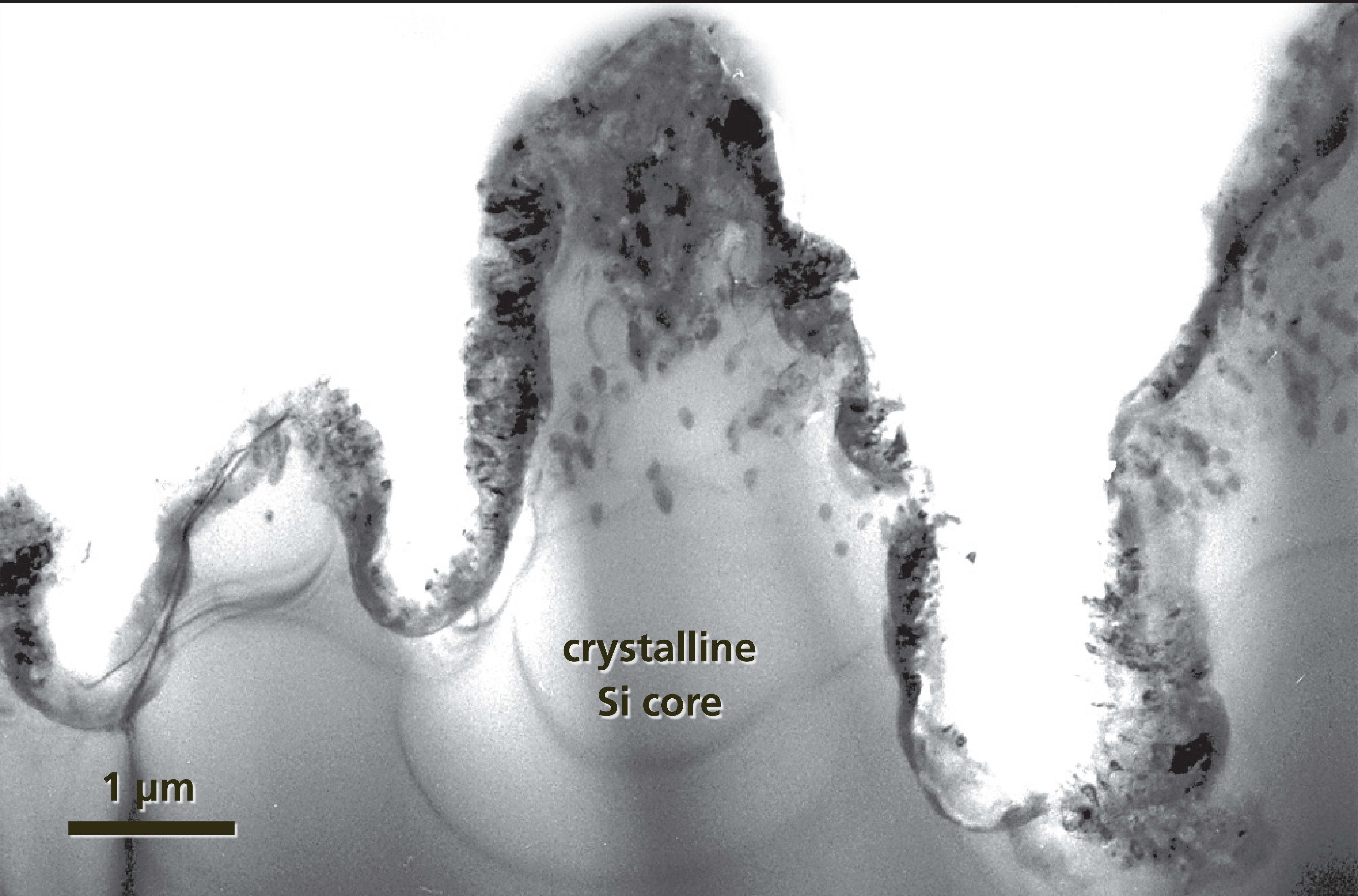
cross-sectional
Transmission Electron
Microscopy



Structure

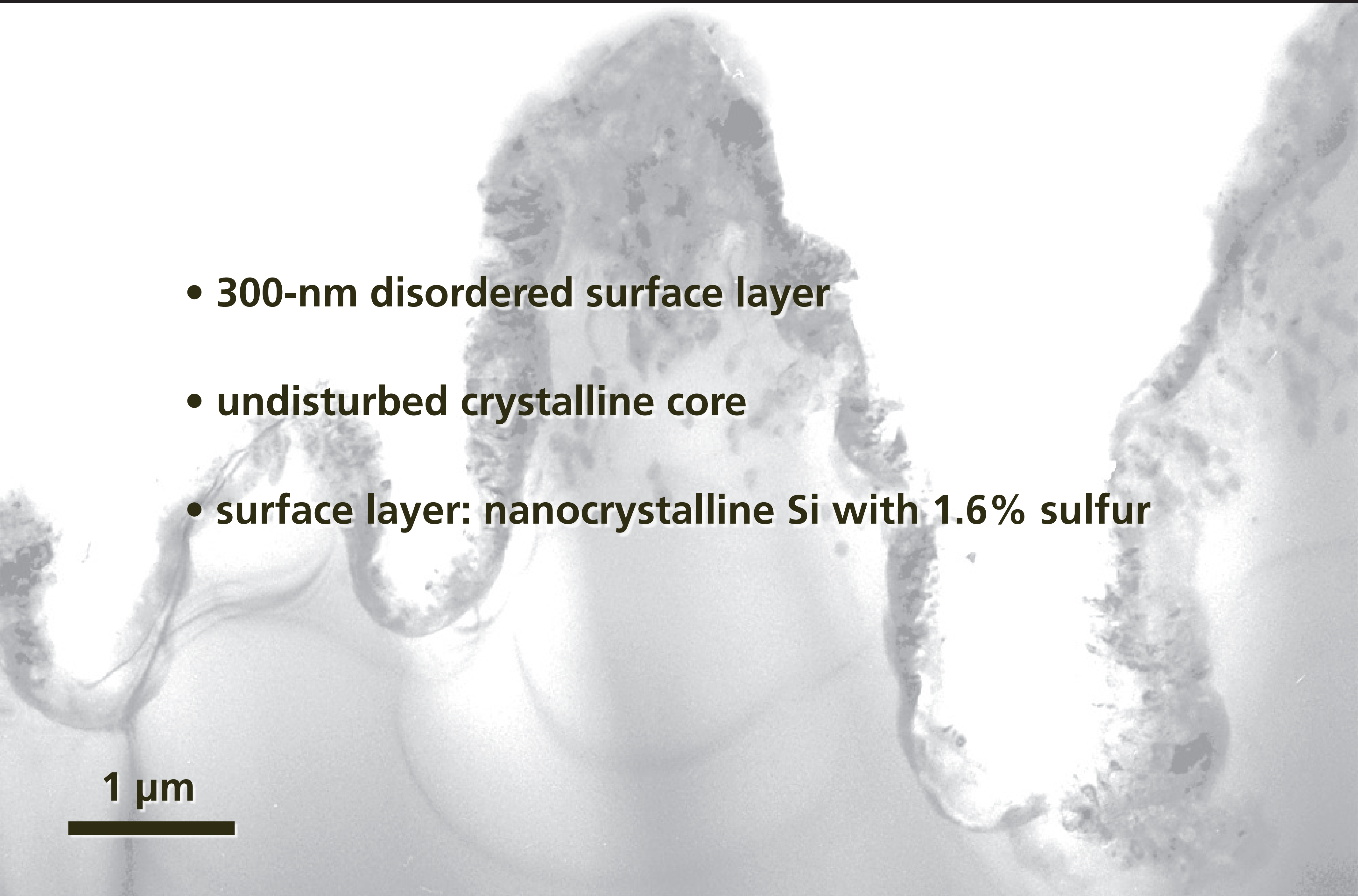


Structure



Structure

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

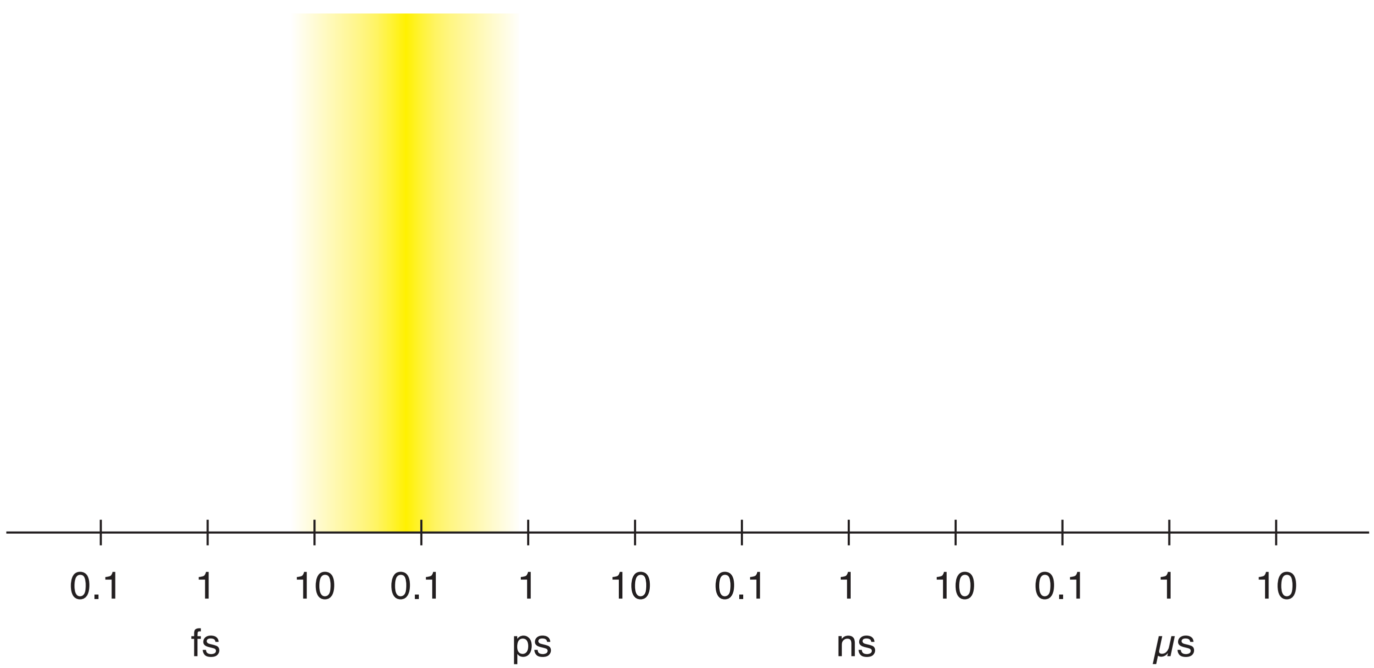


Structure

two processes: melting and ablation

Structure

relevant time scales



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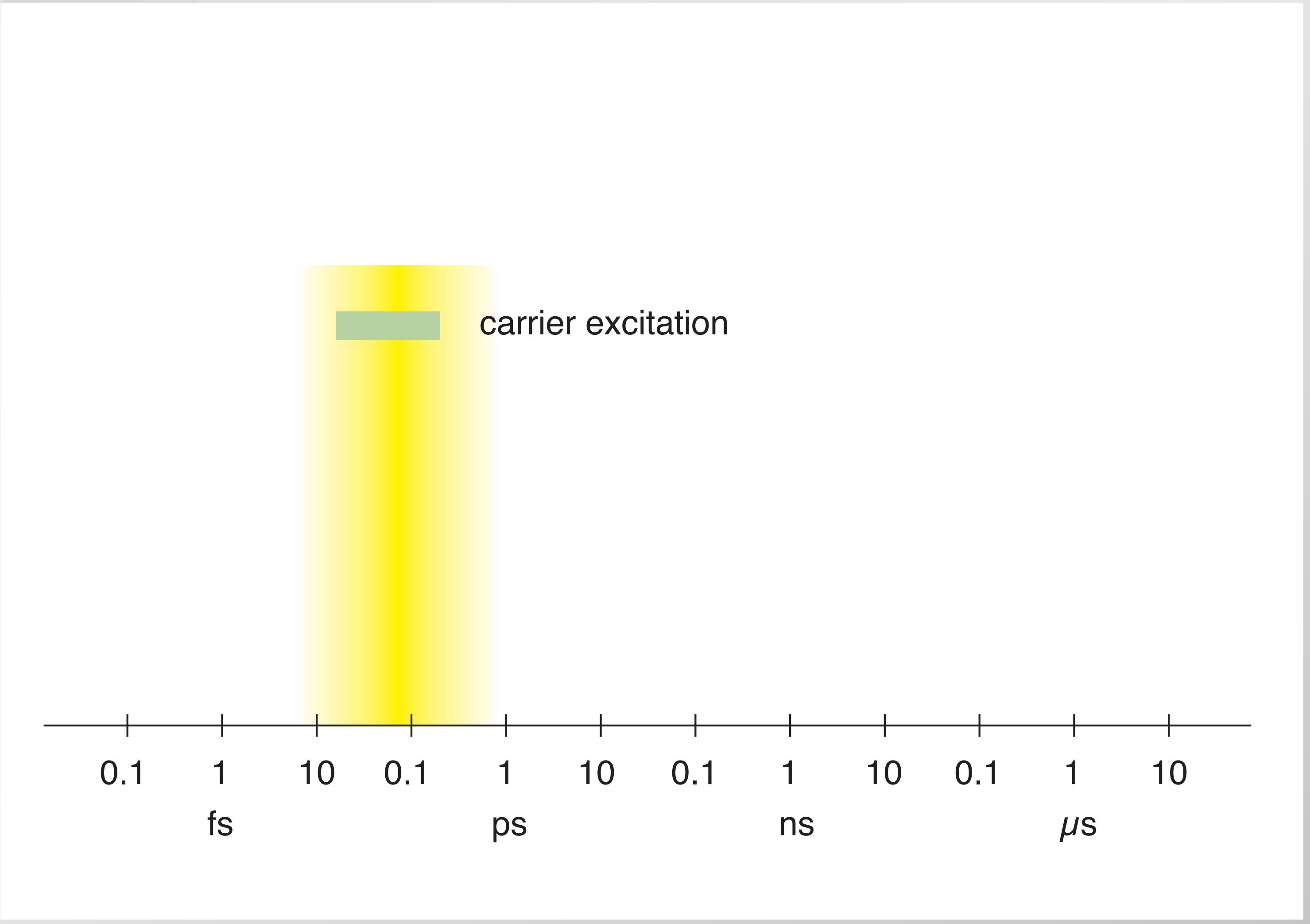

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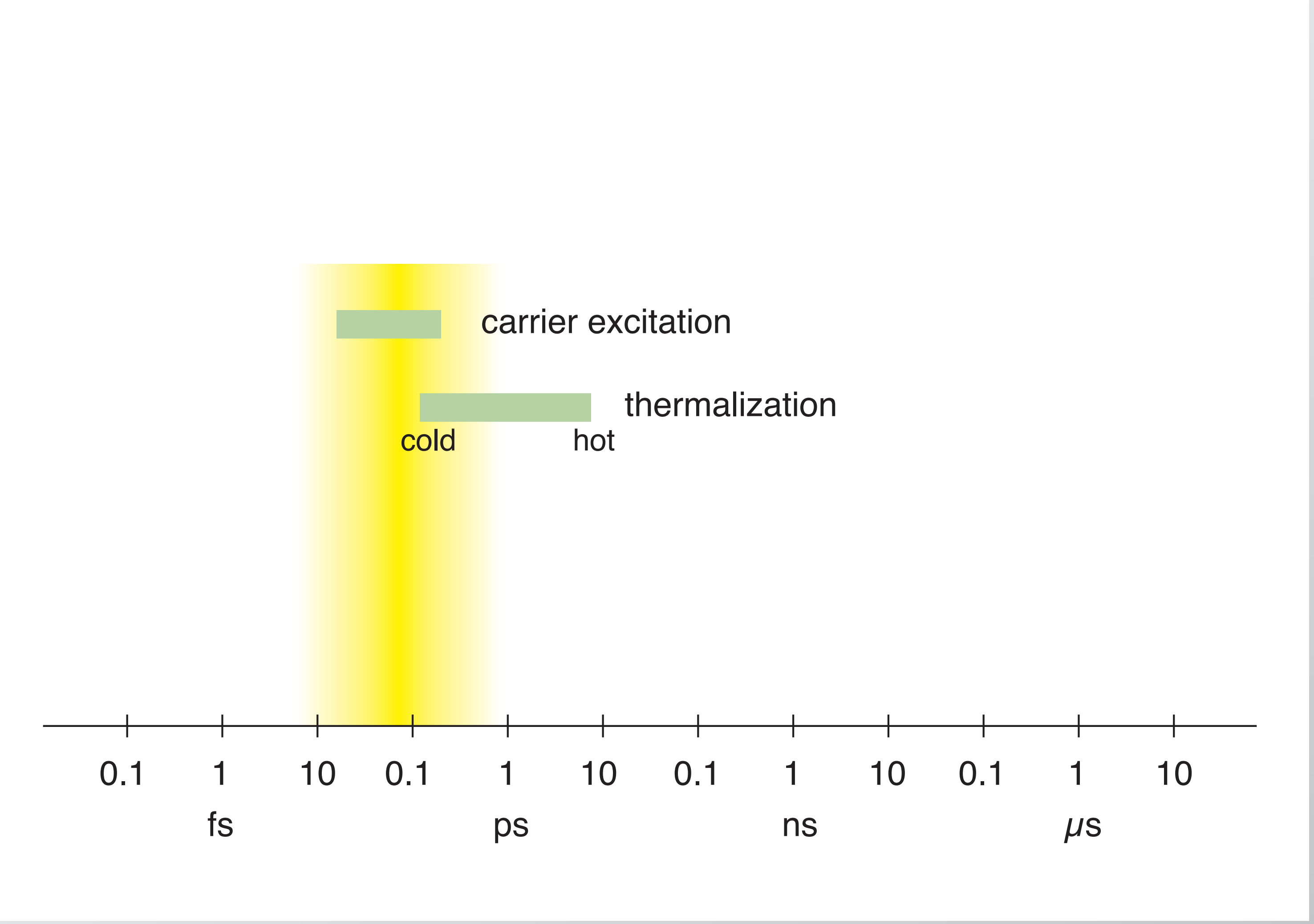

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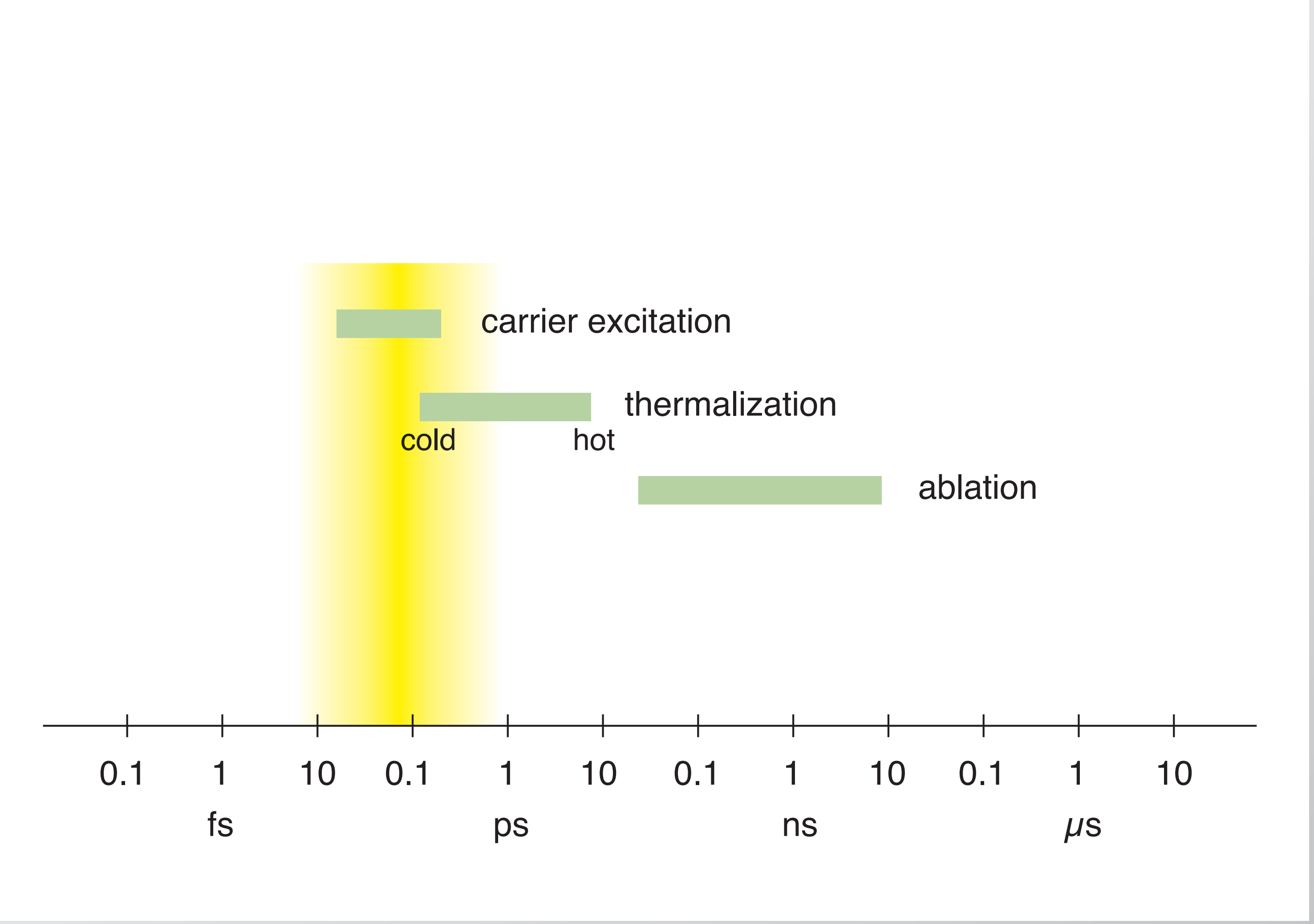

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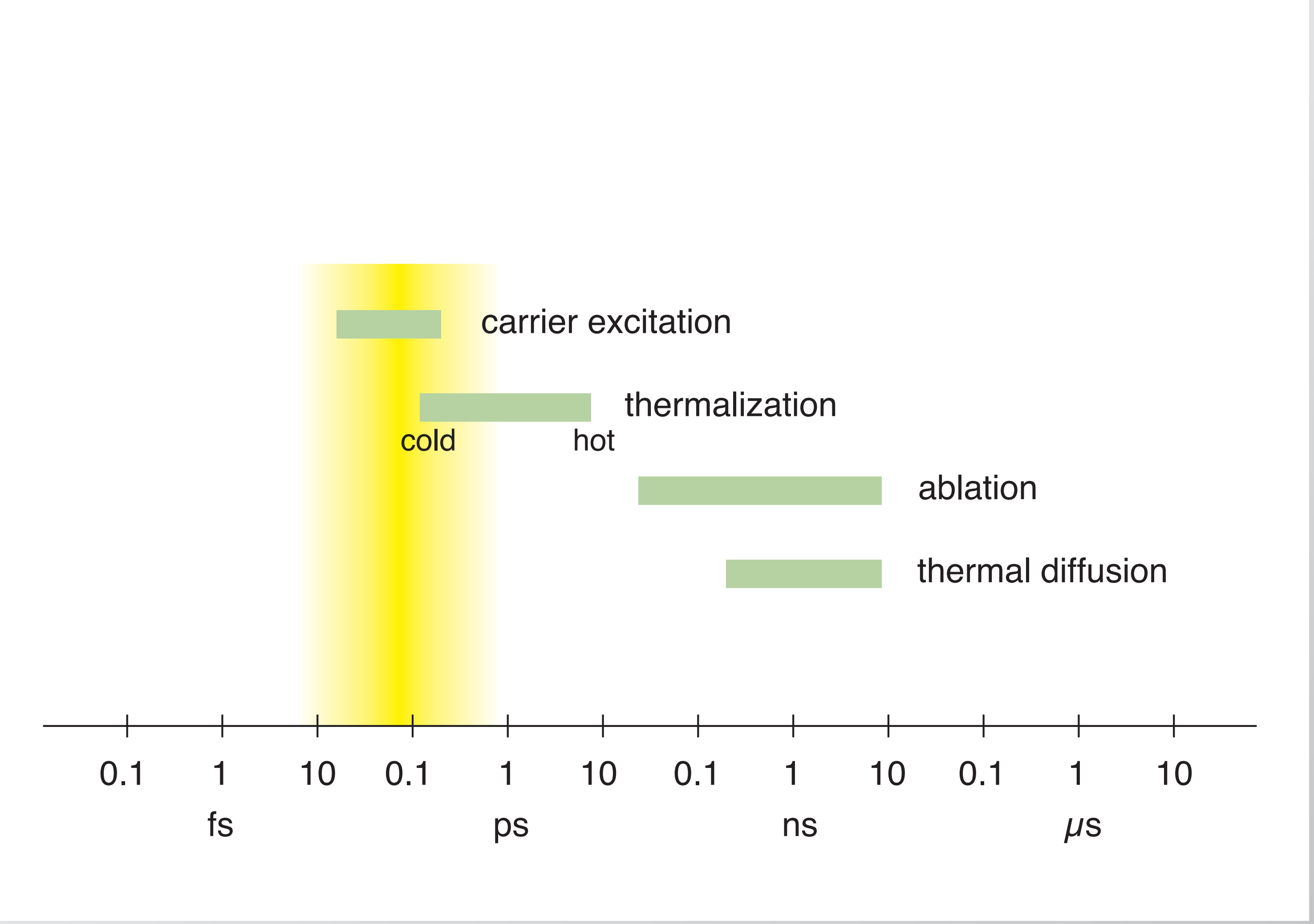

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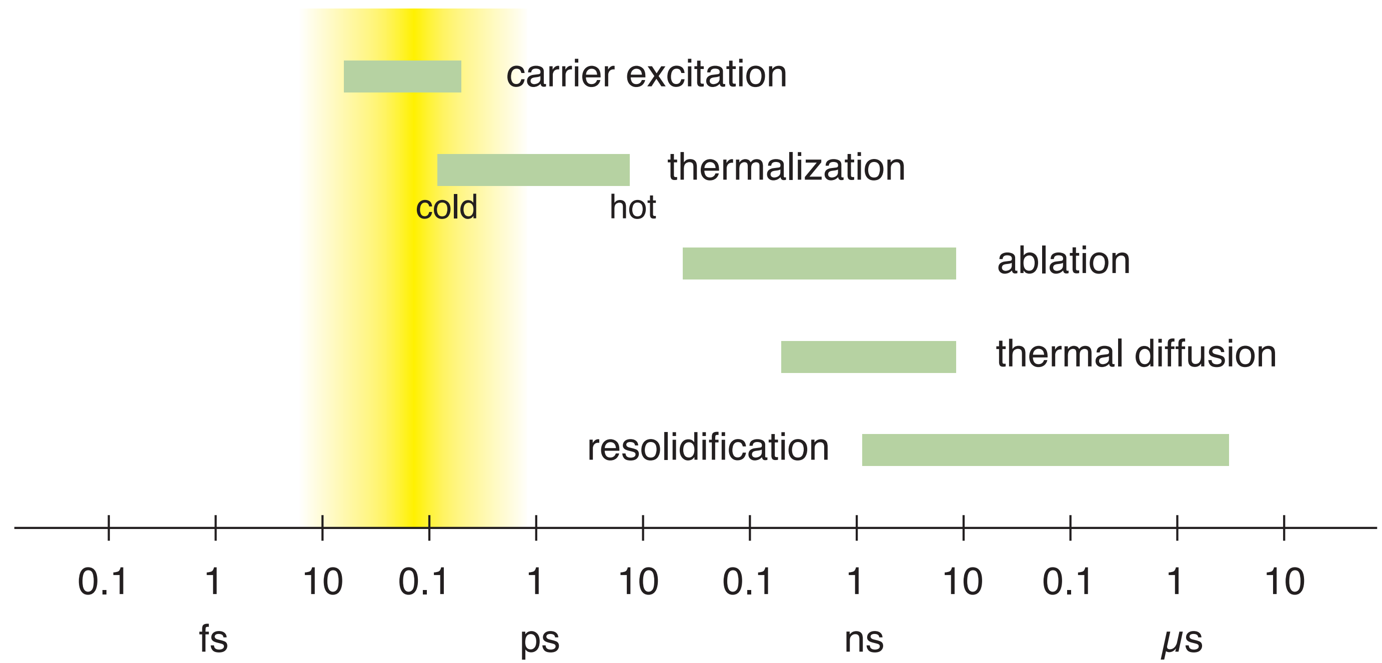

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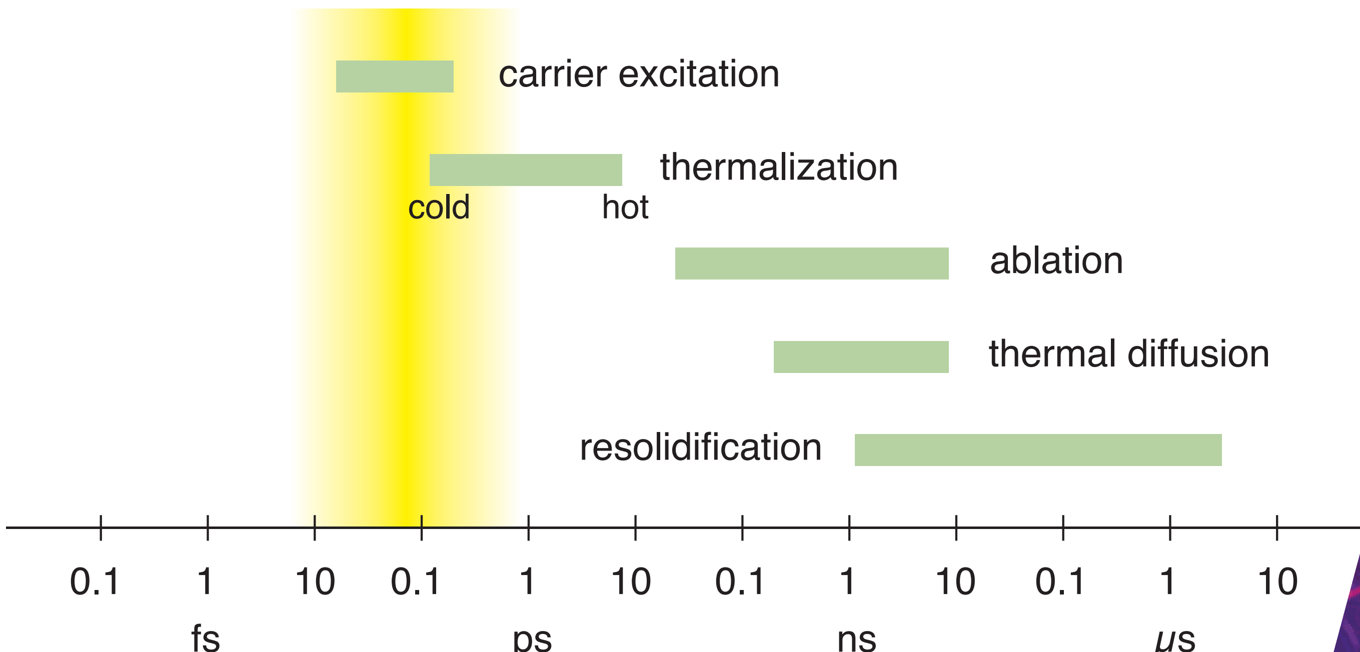
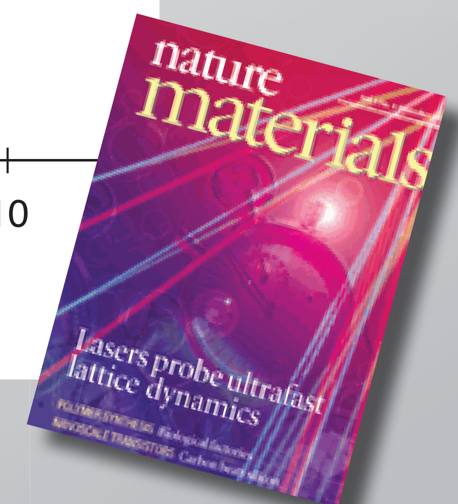


Nature Materials **1**, 217 (2002)



Structure

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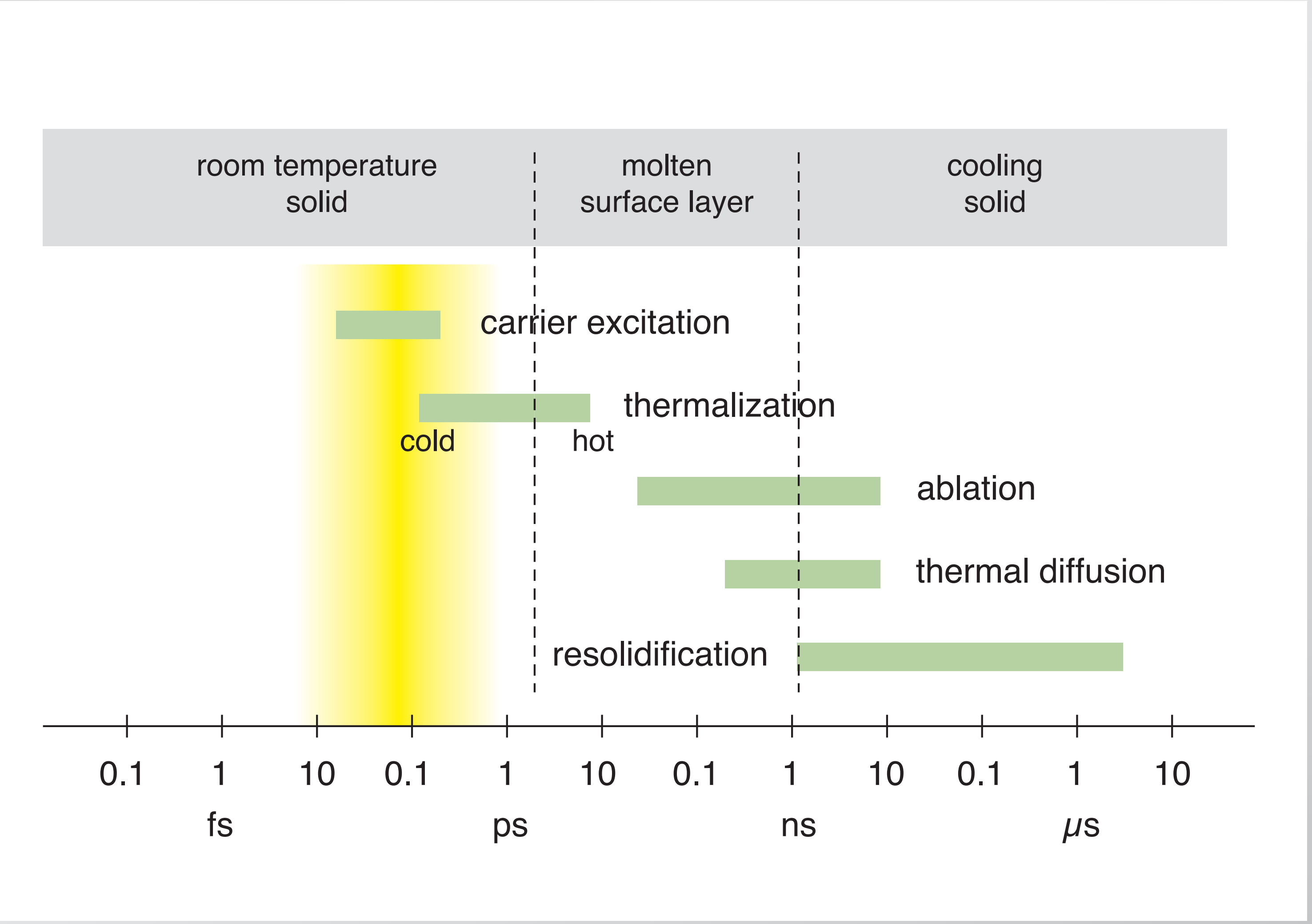

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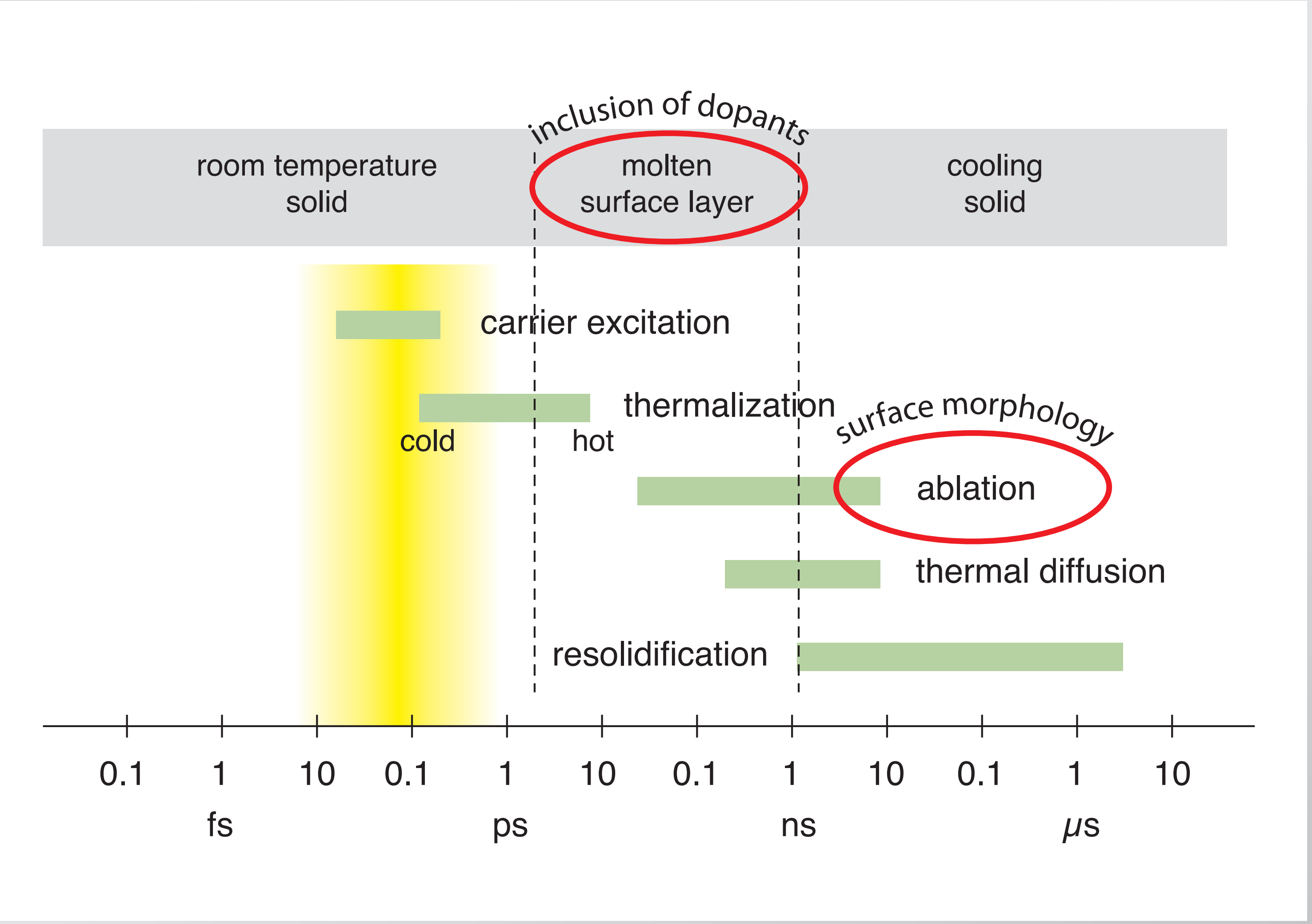
relevant time scales



Structure

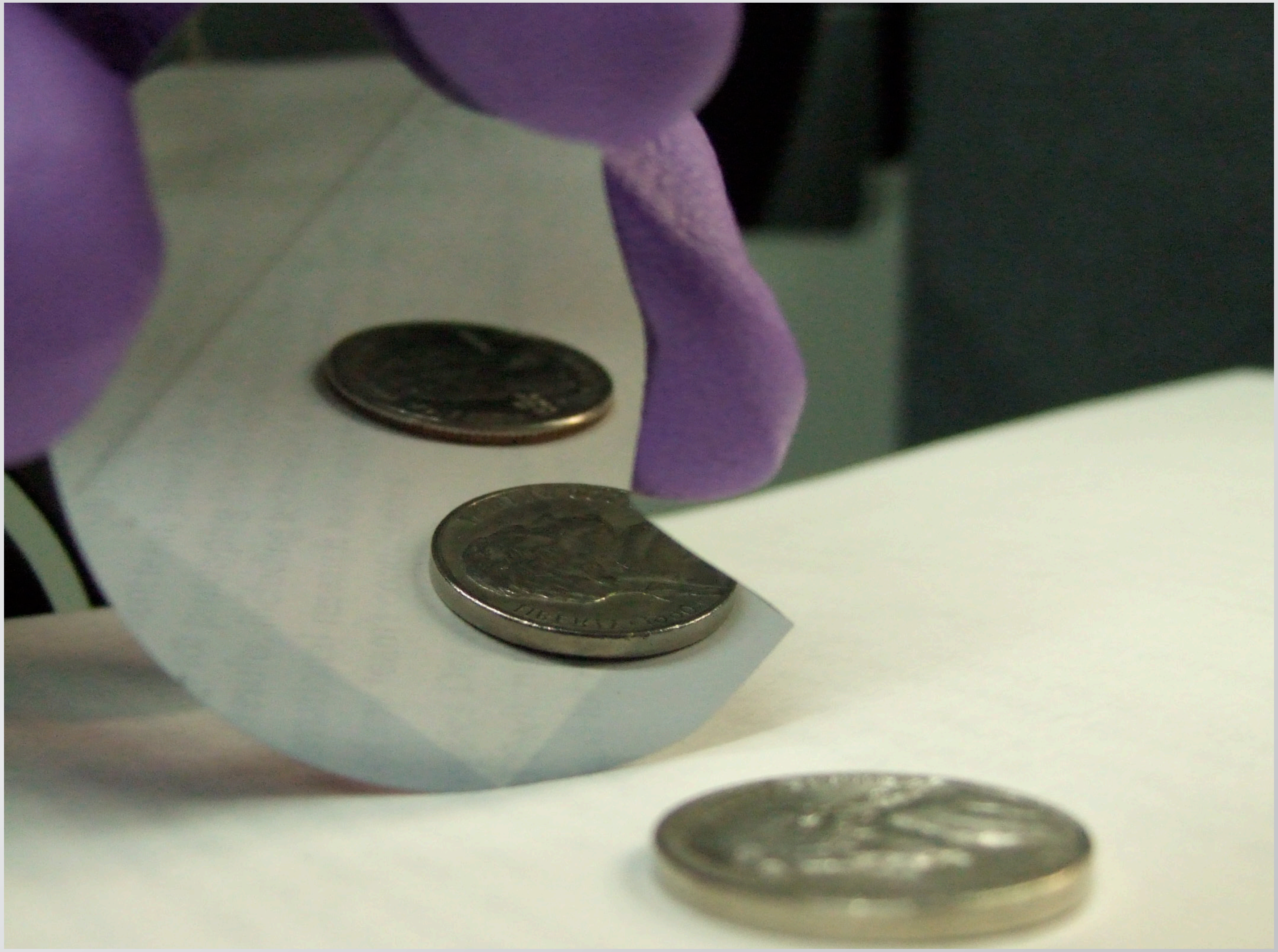
different thresholds:

melting: 1.5 kJ/m^2

ablation: 3.1 kJ/m^2

Structure

decouple ablation from melting



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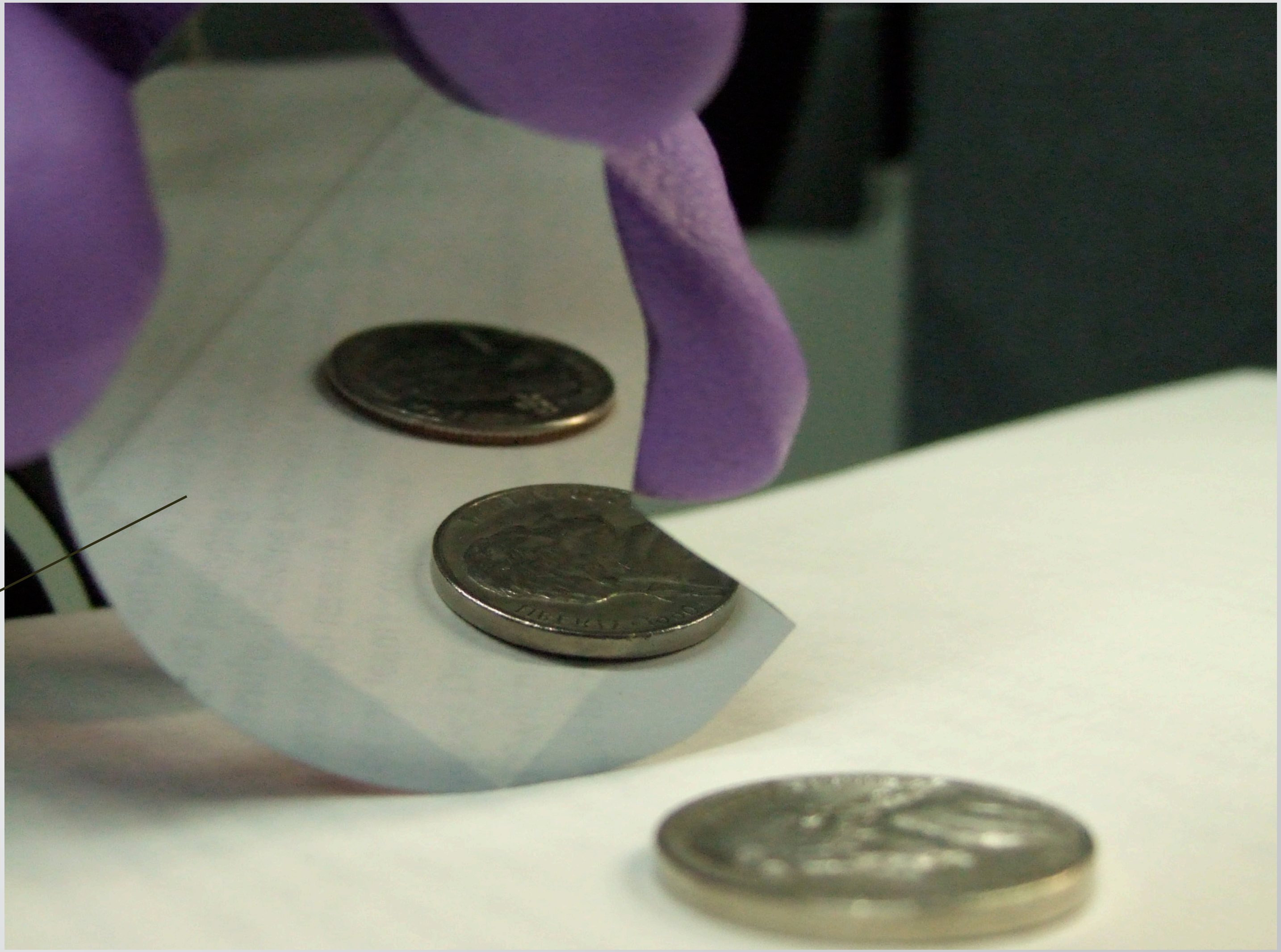
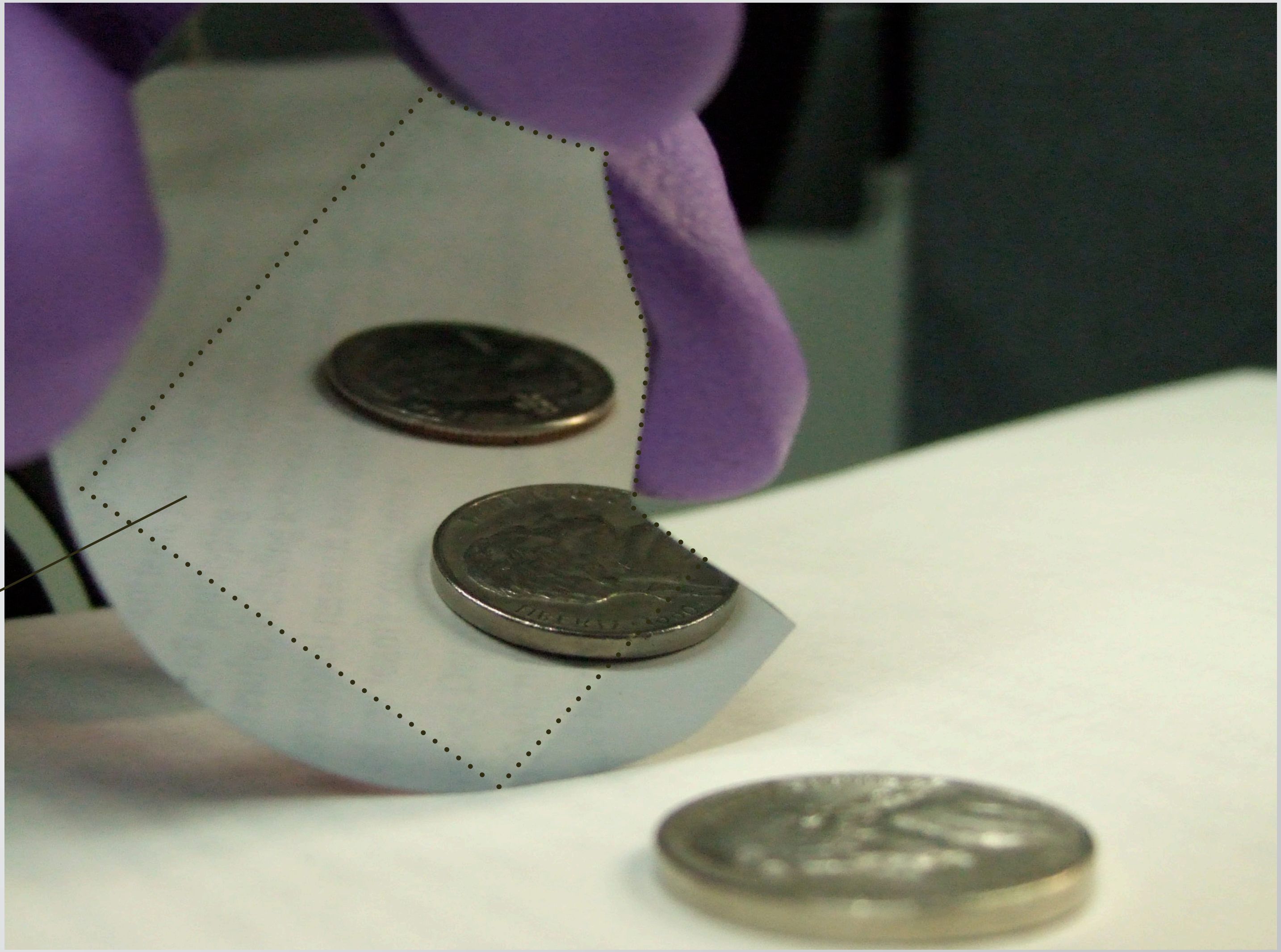


doped

Structure

decouple ablation from melting

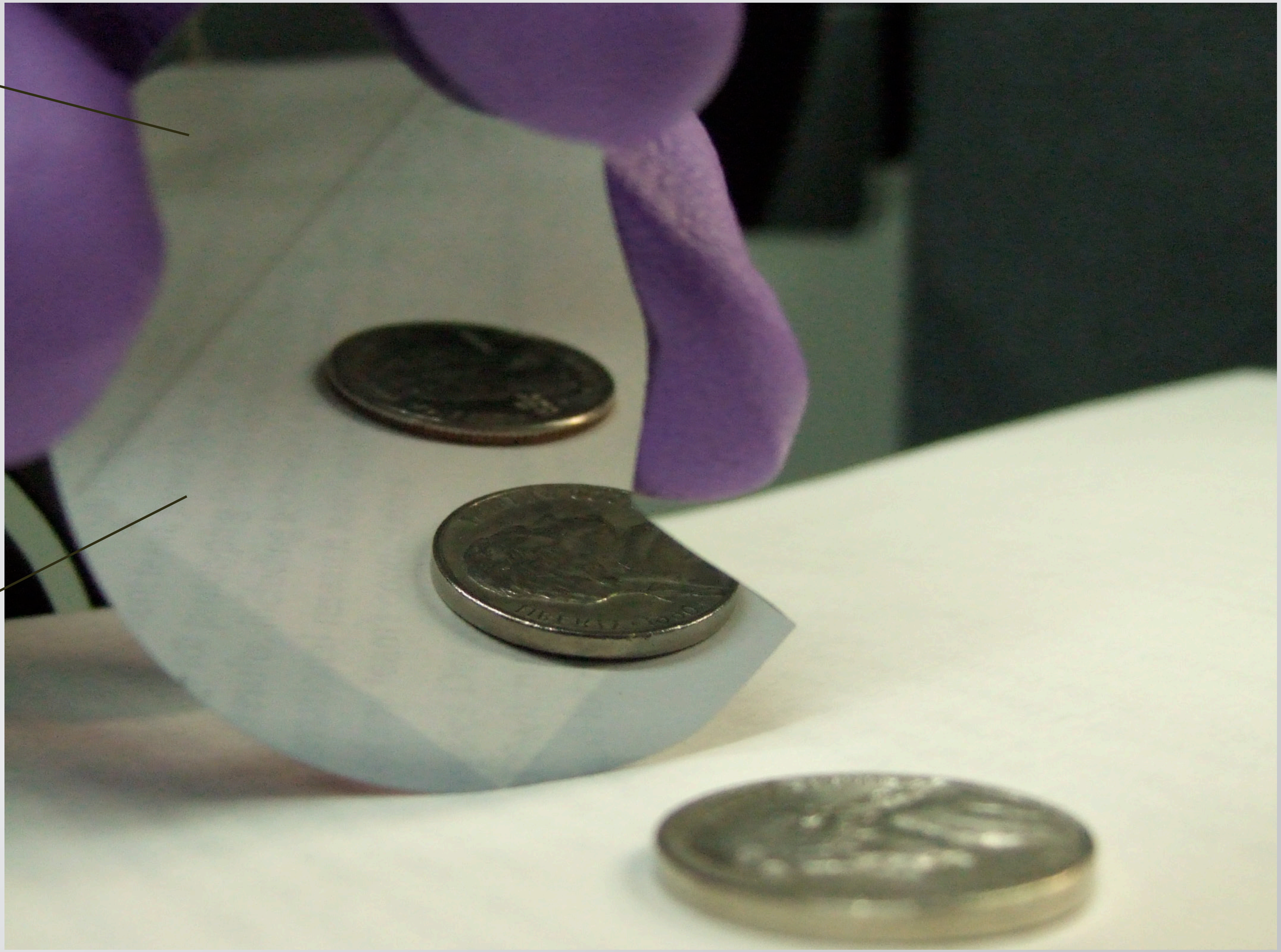


Structure

decouple ablation from melting

undoped

doped



Structure

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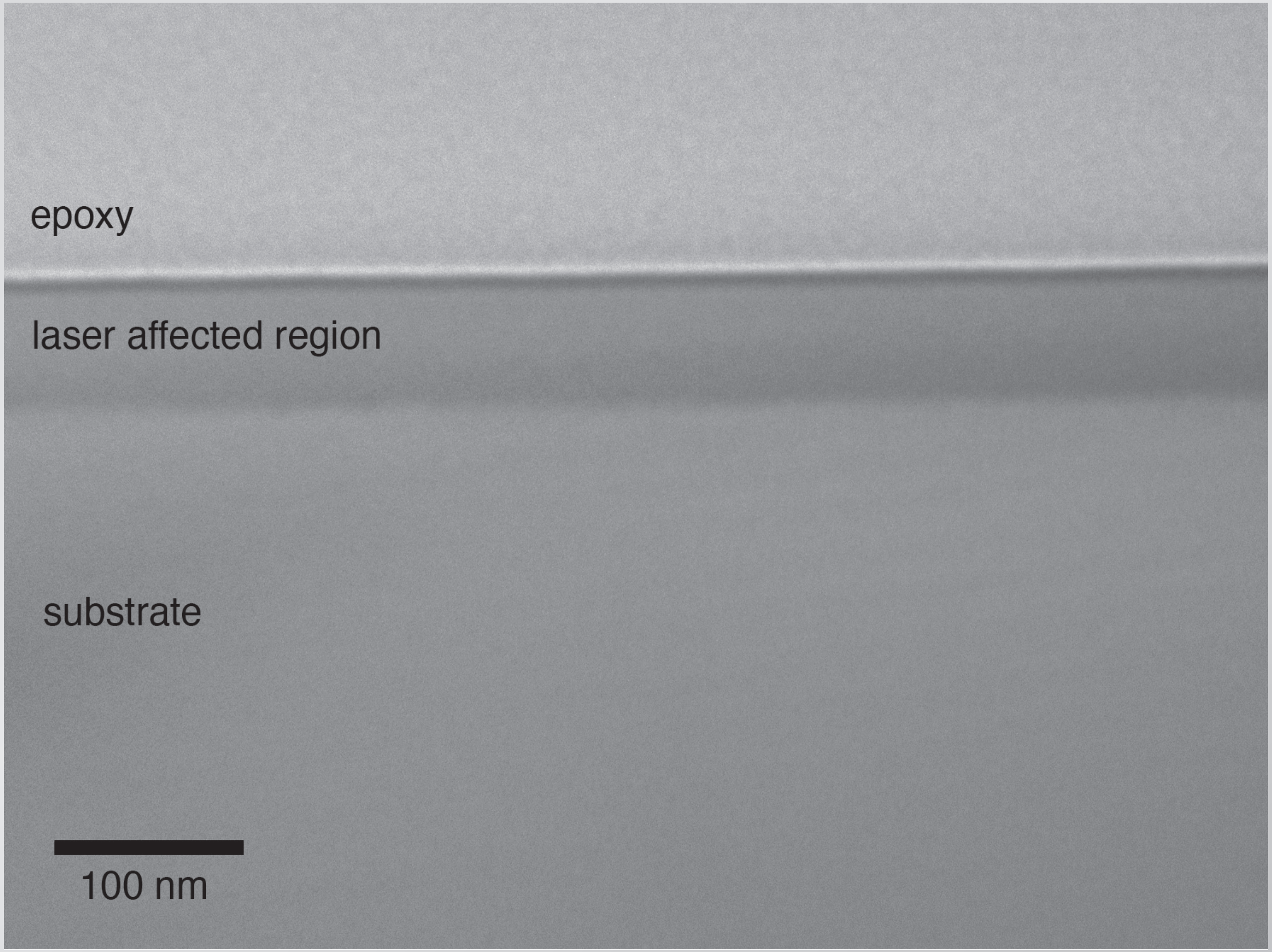

Structure

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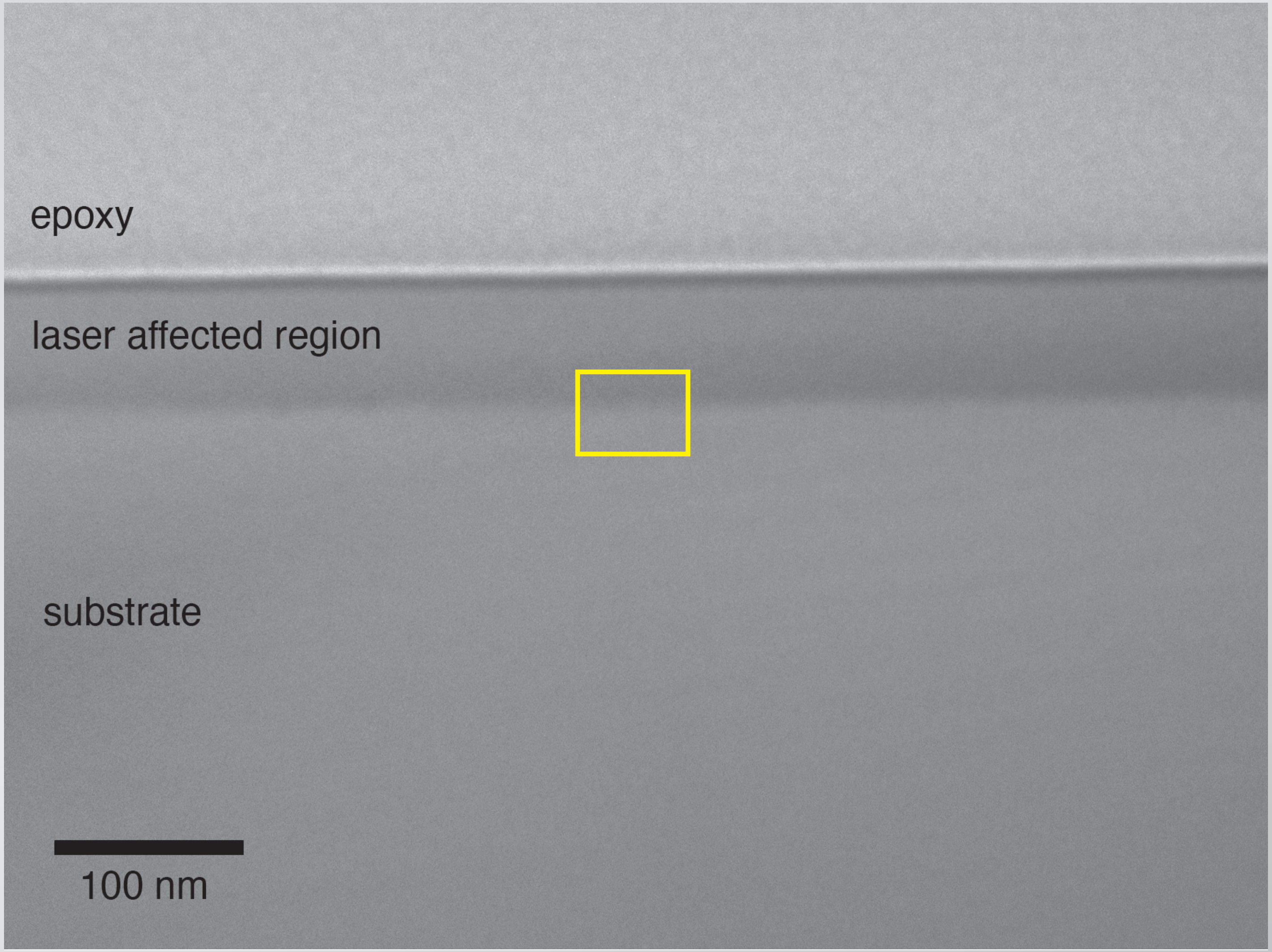

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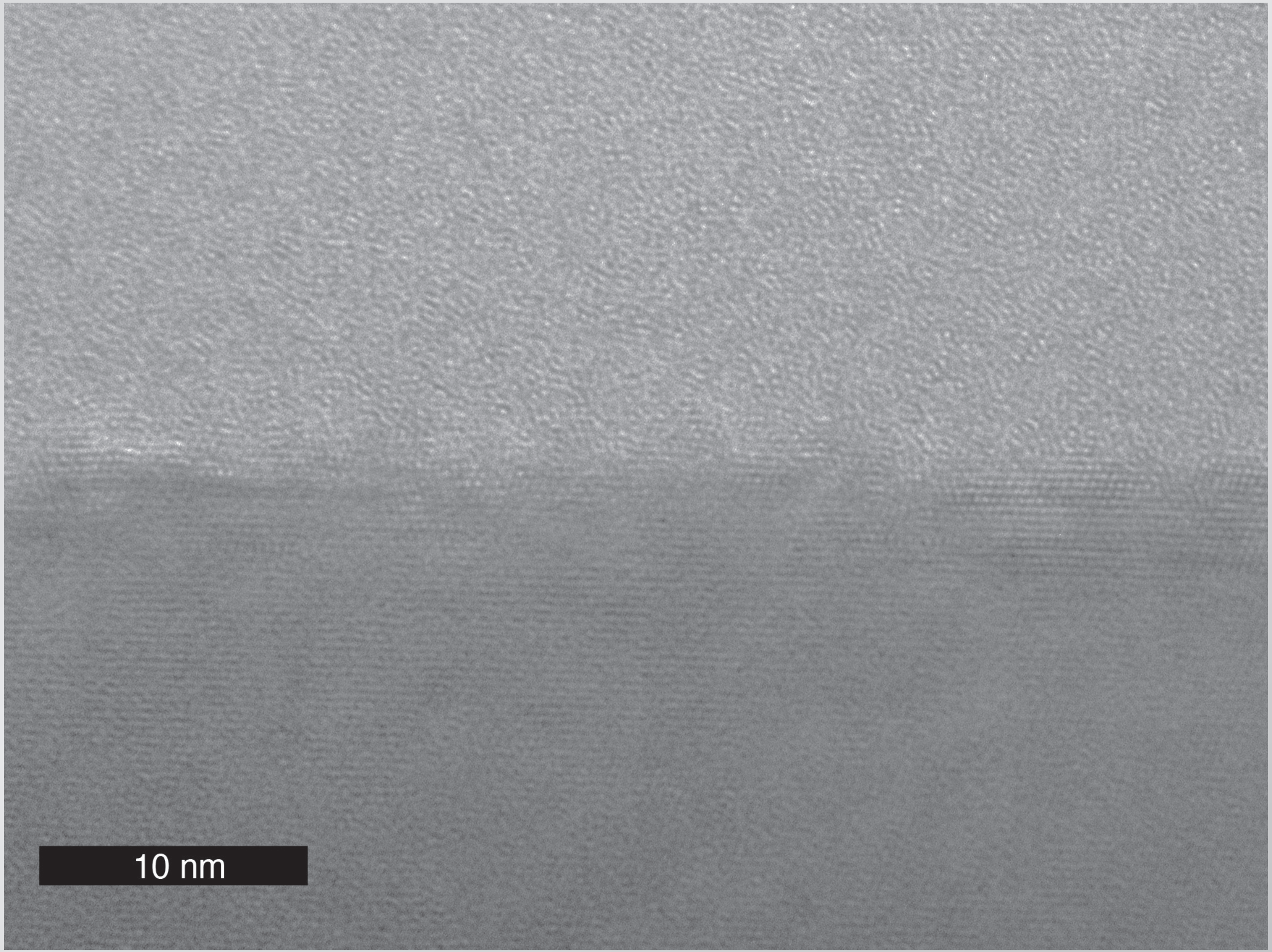
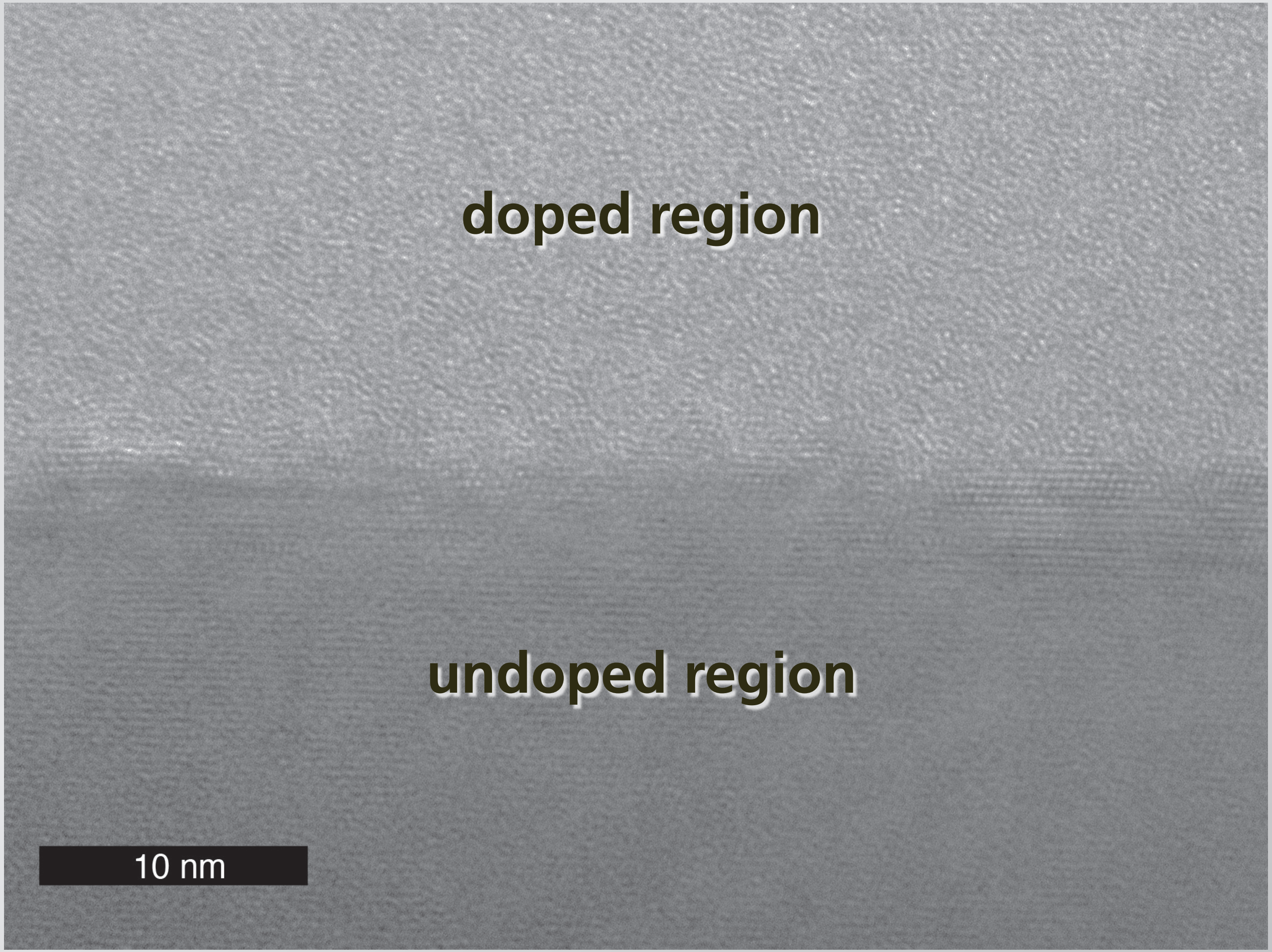


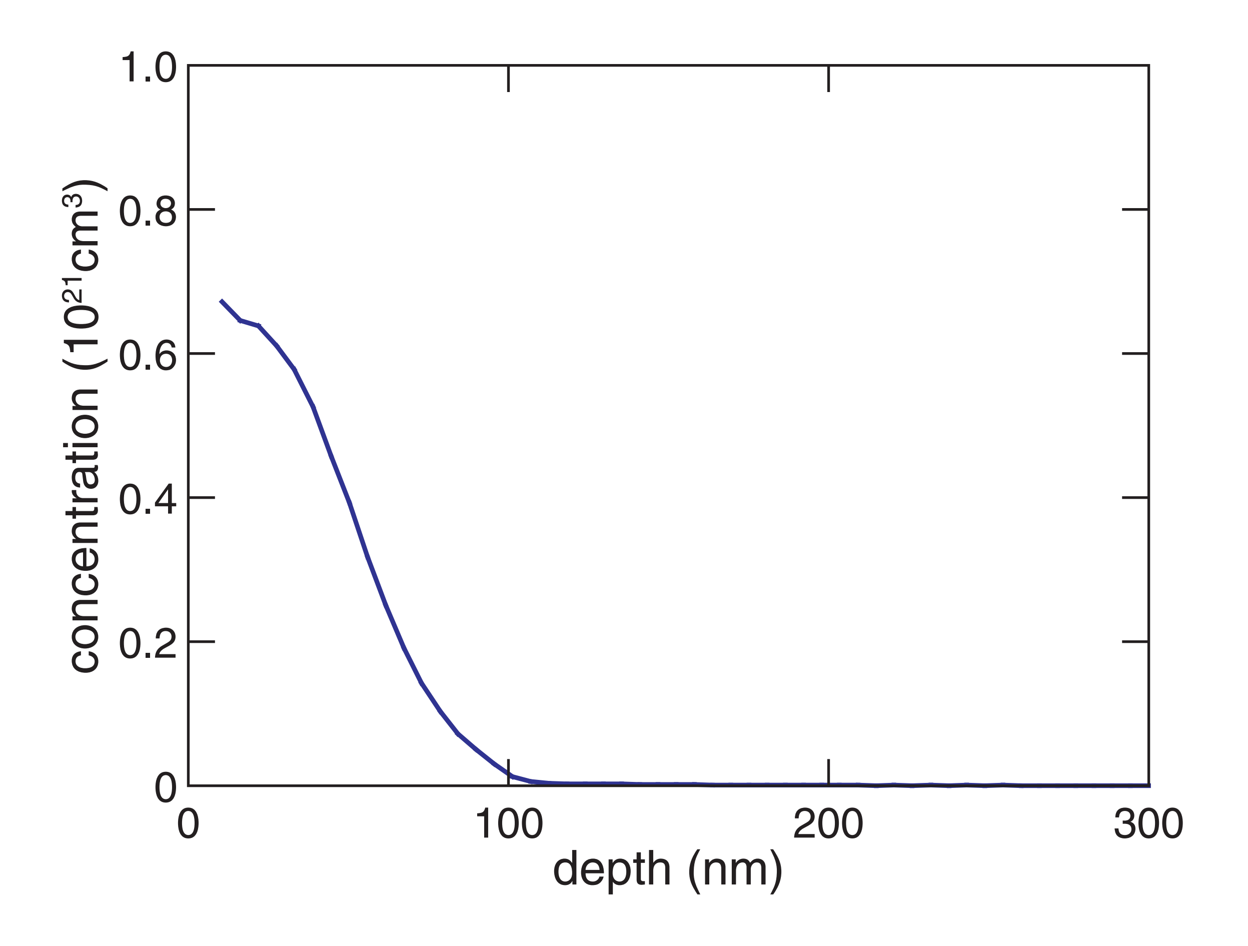
Structure

decouple ablation from melting



Structure

secondary ion mass spectrometry



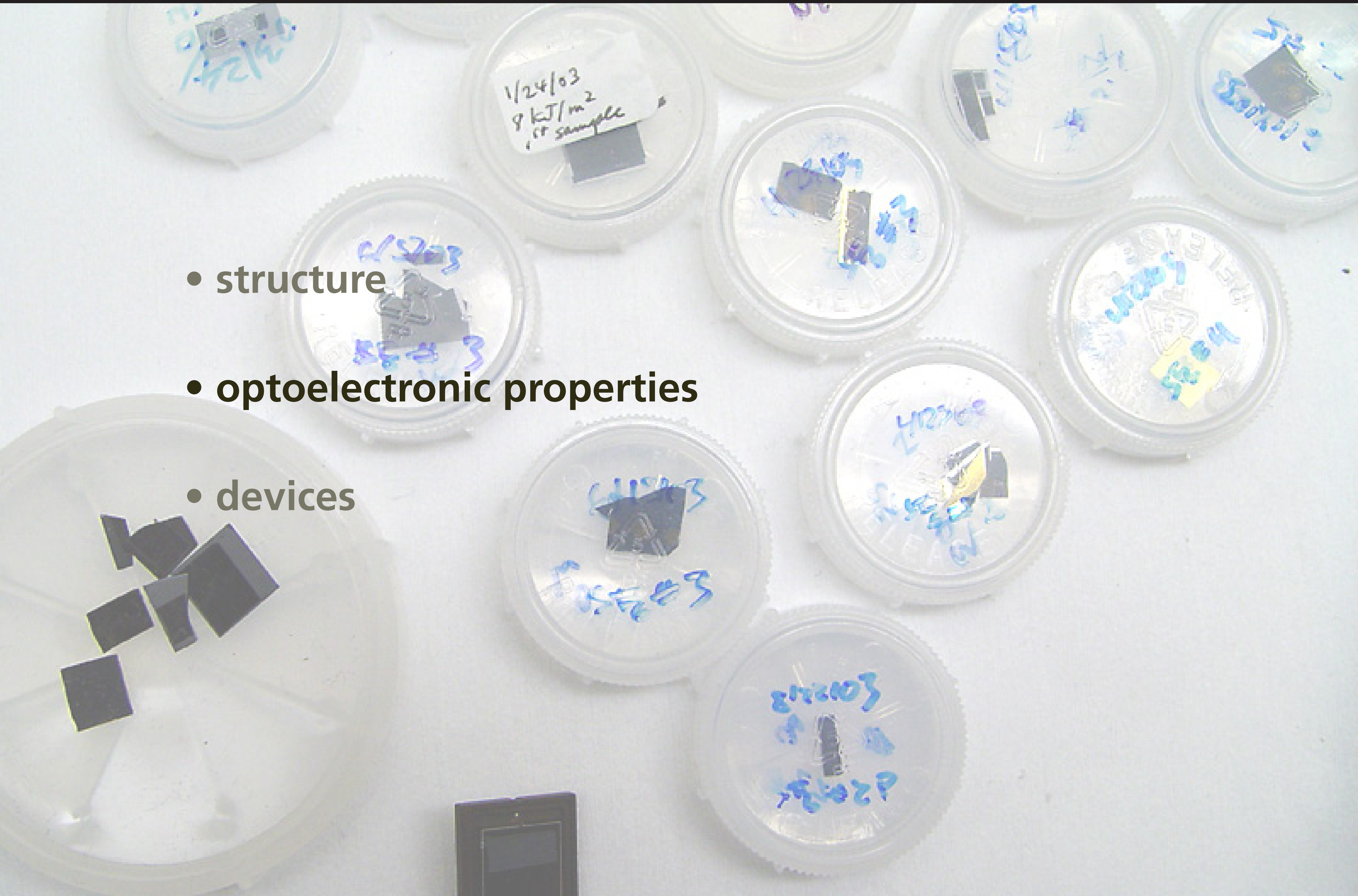
Structure

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

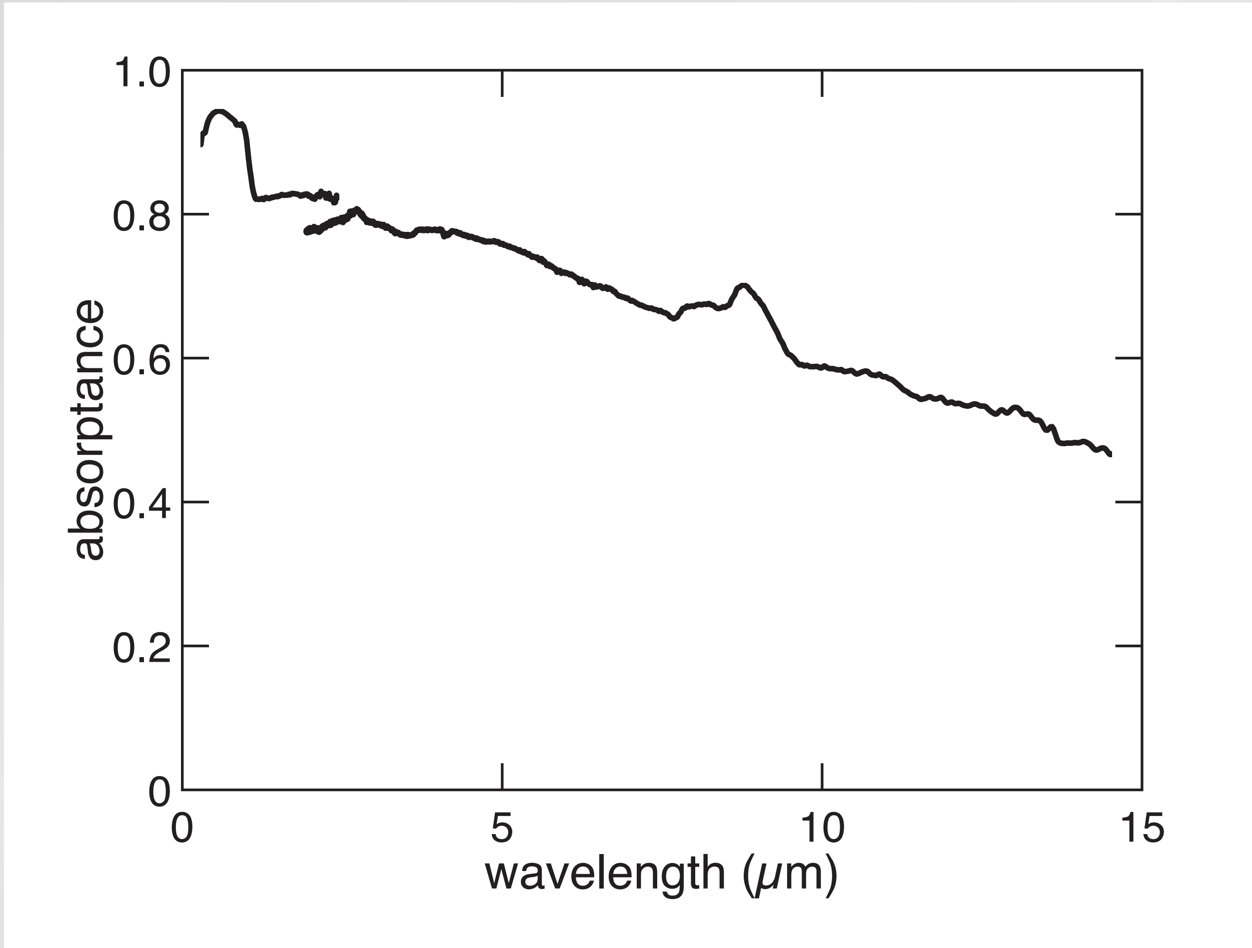
Outline

- structure
- optoelectronic properties
- devices



Optoelectronic properties

absorptance (1 – R_{int} – T_{int})



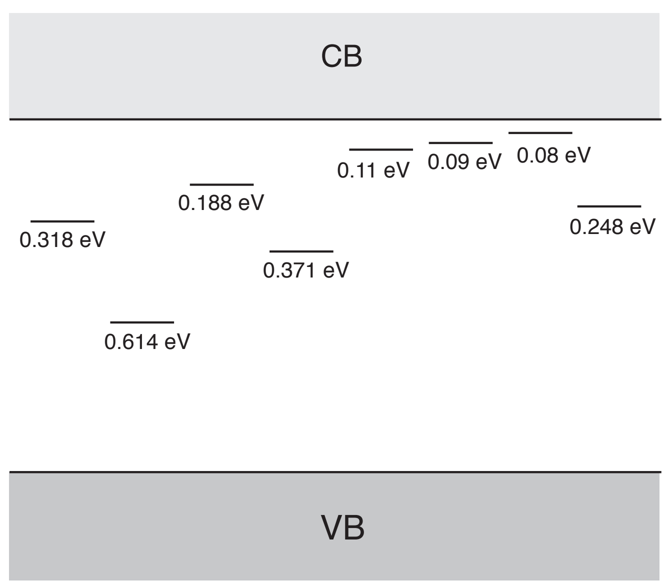
Asenbaum, Vienna

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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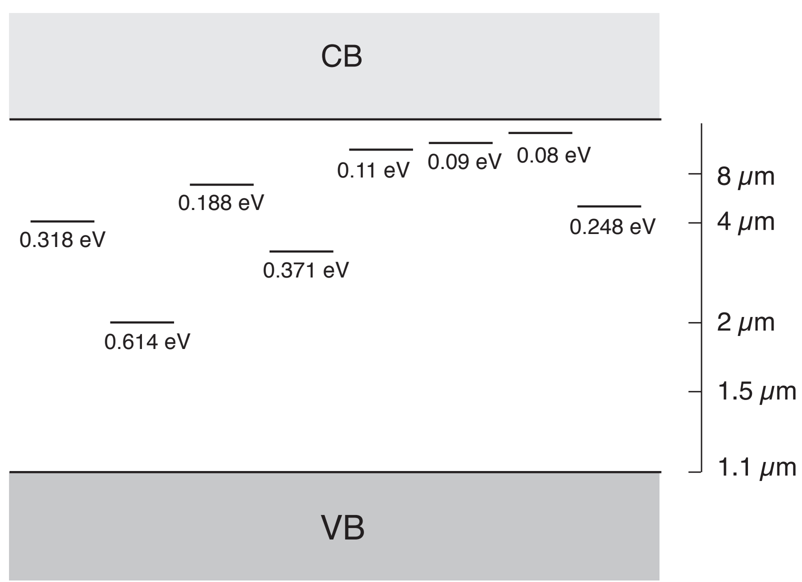
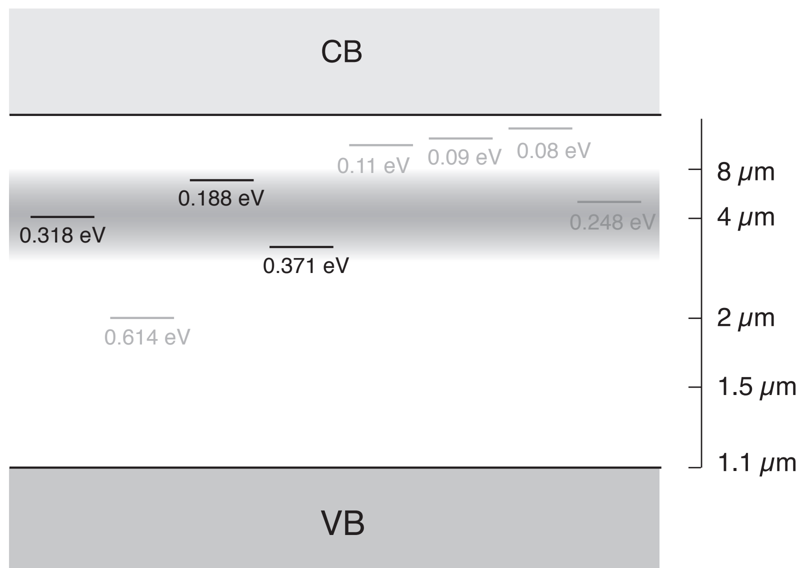


Janzén *et al.*, Phys. Rev. B 29, 1907 (1984)

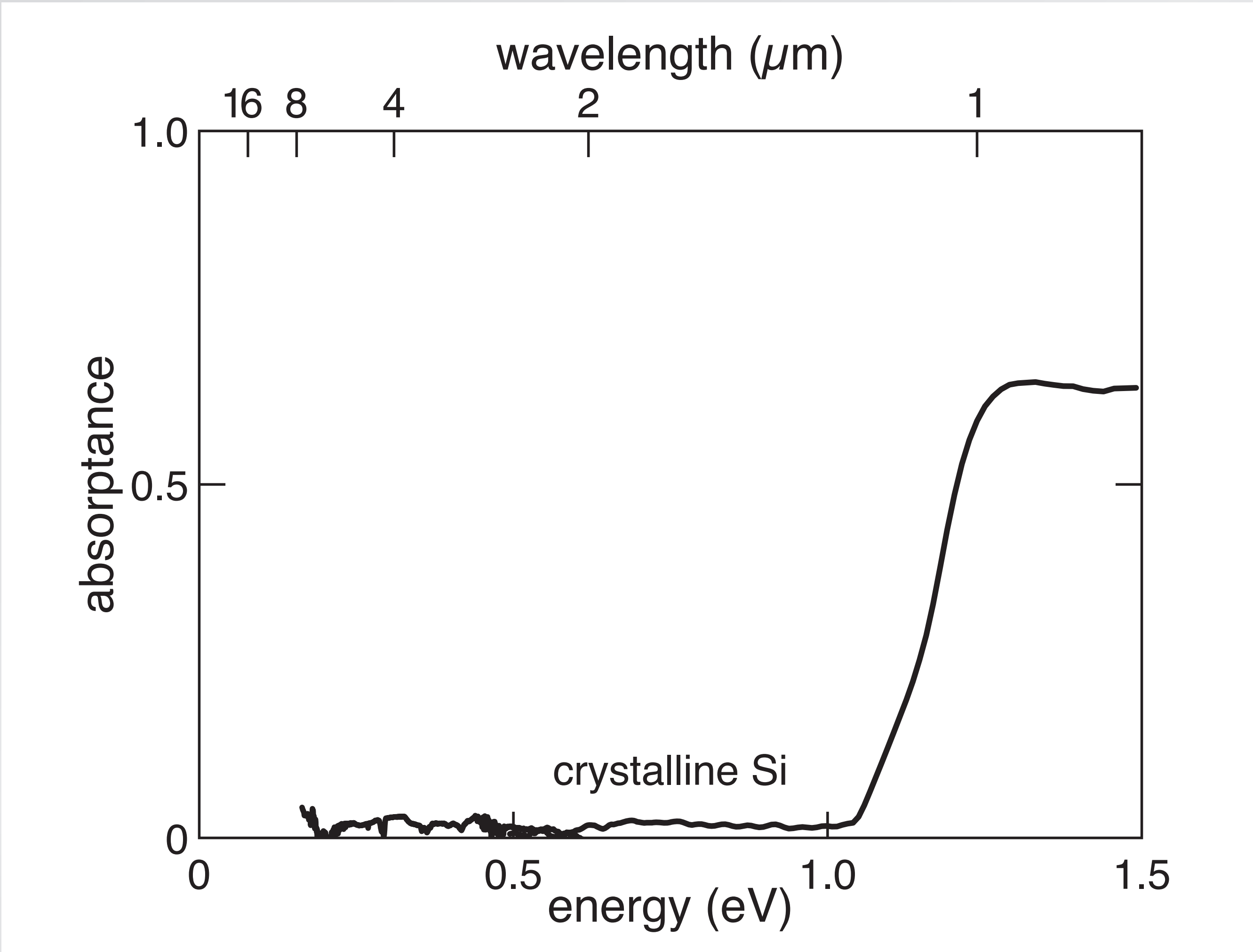
Optoelectronic properties

at high concentration states broaden into band



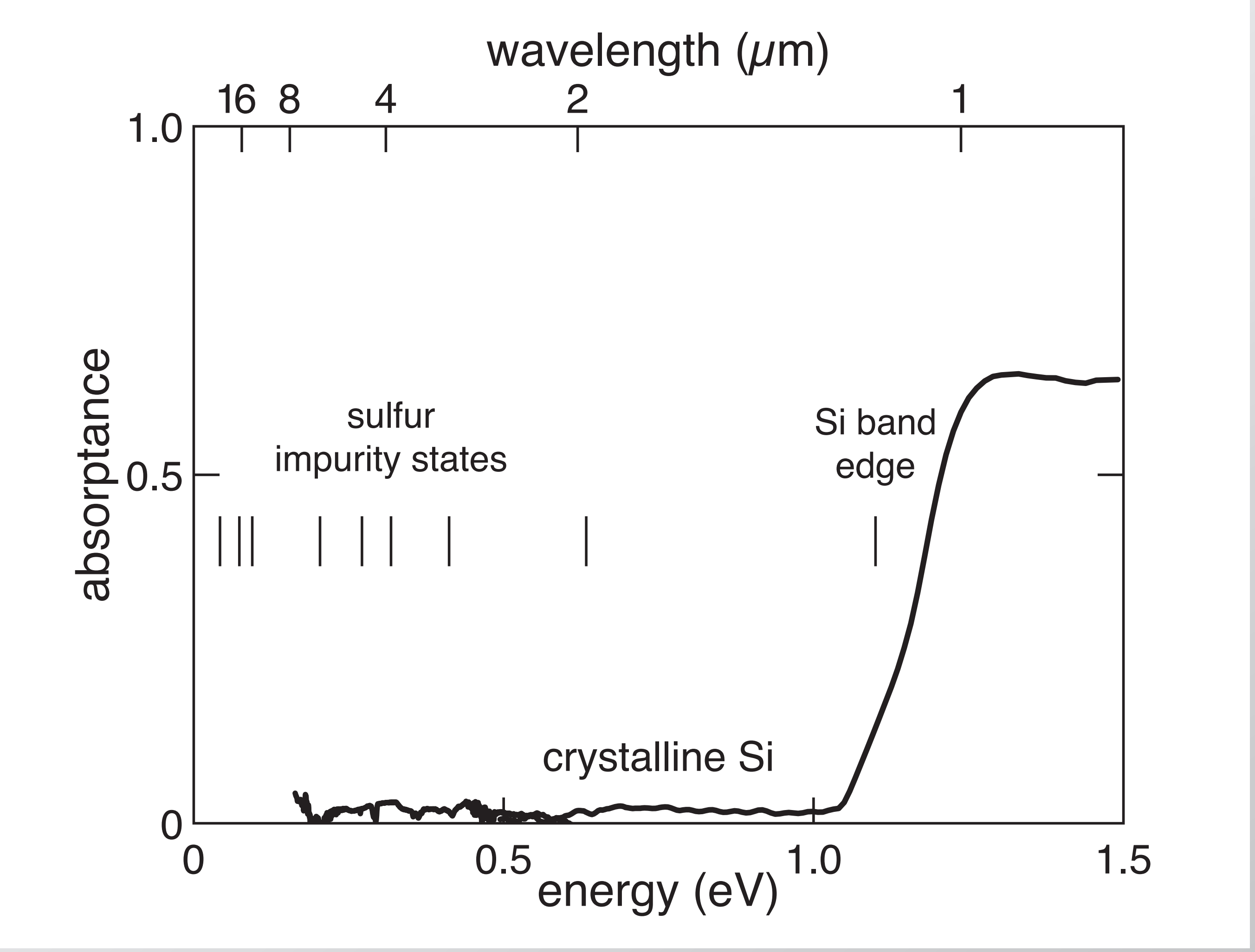
Optoelectronic properties

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



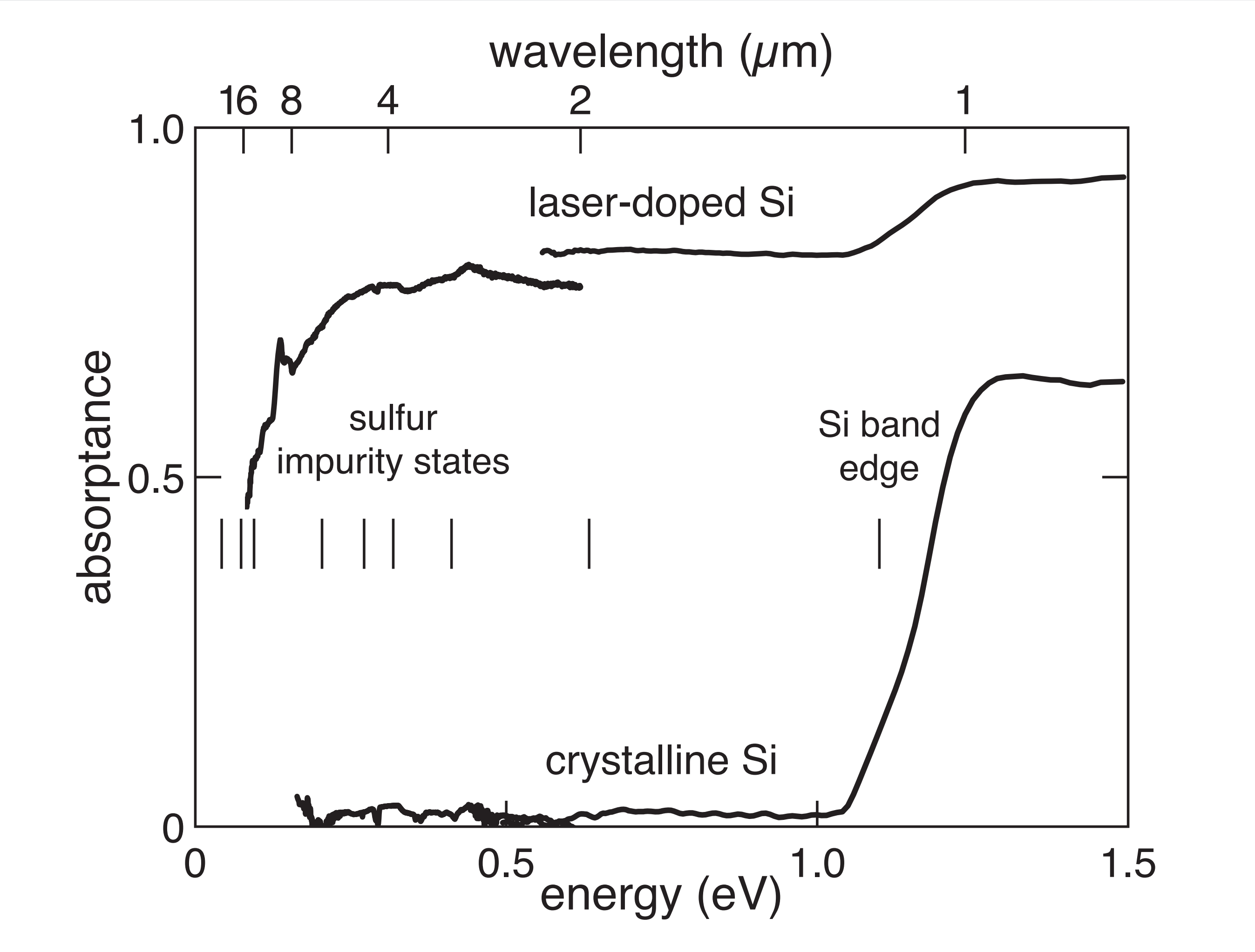
Optoelectronic properties

10^{-6} sulfur doping



Optoelectronic properties

laser-doped S:Si



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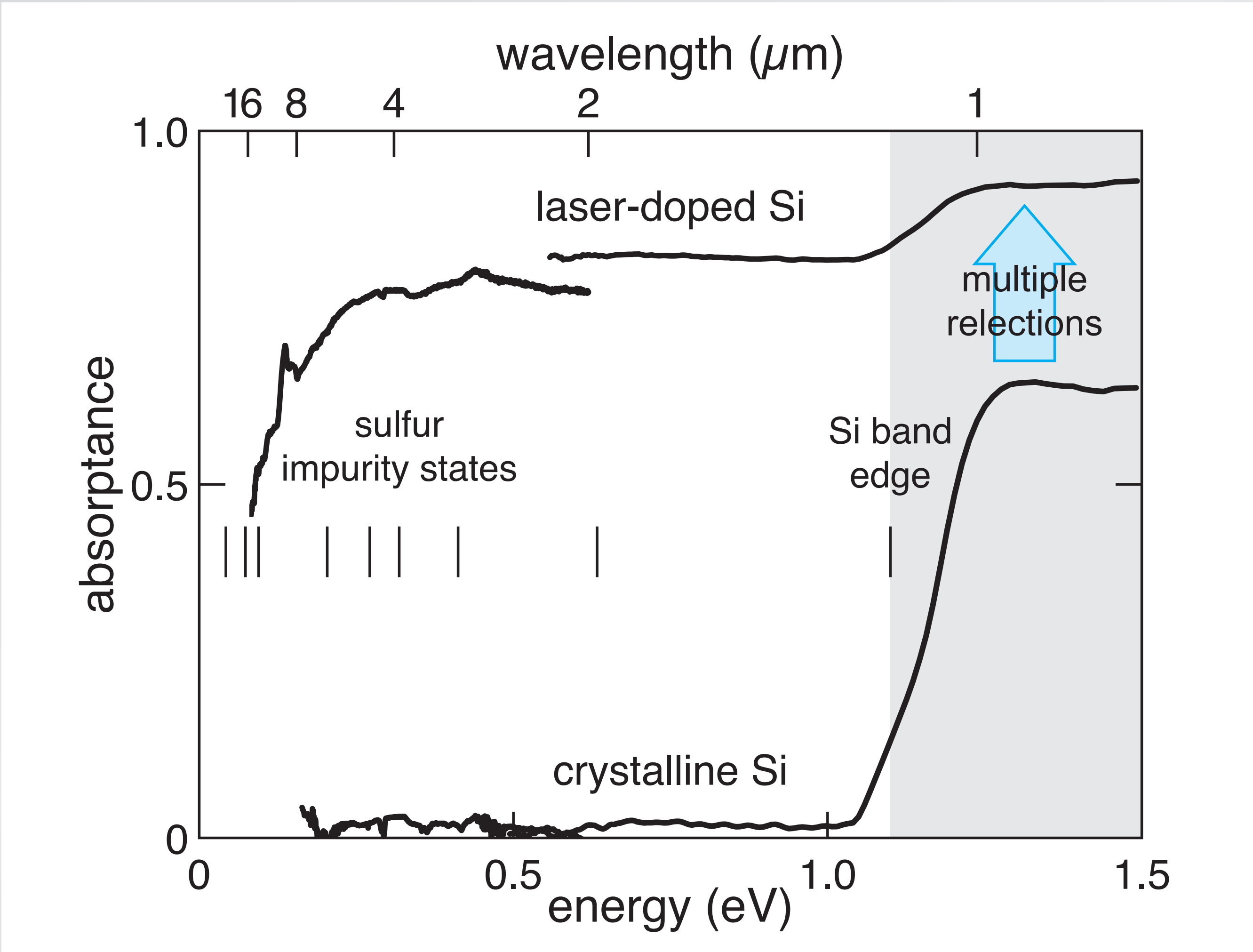

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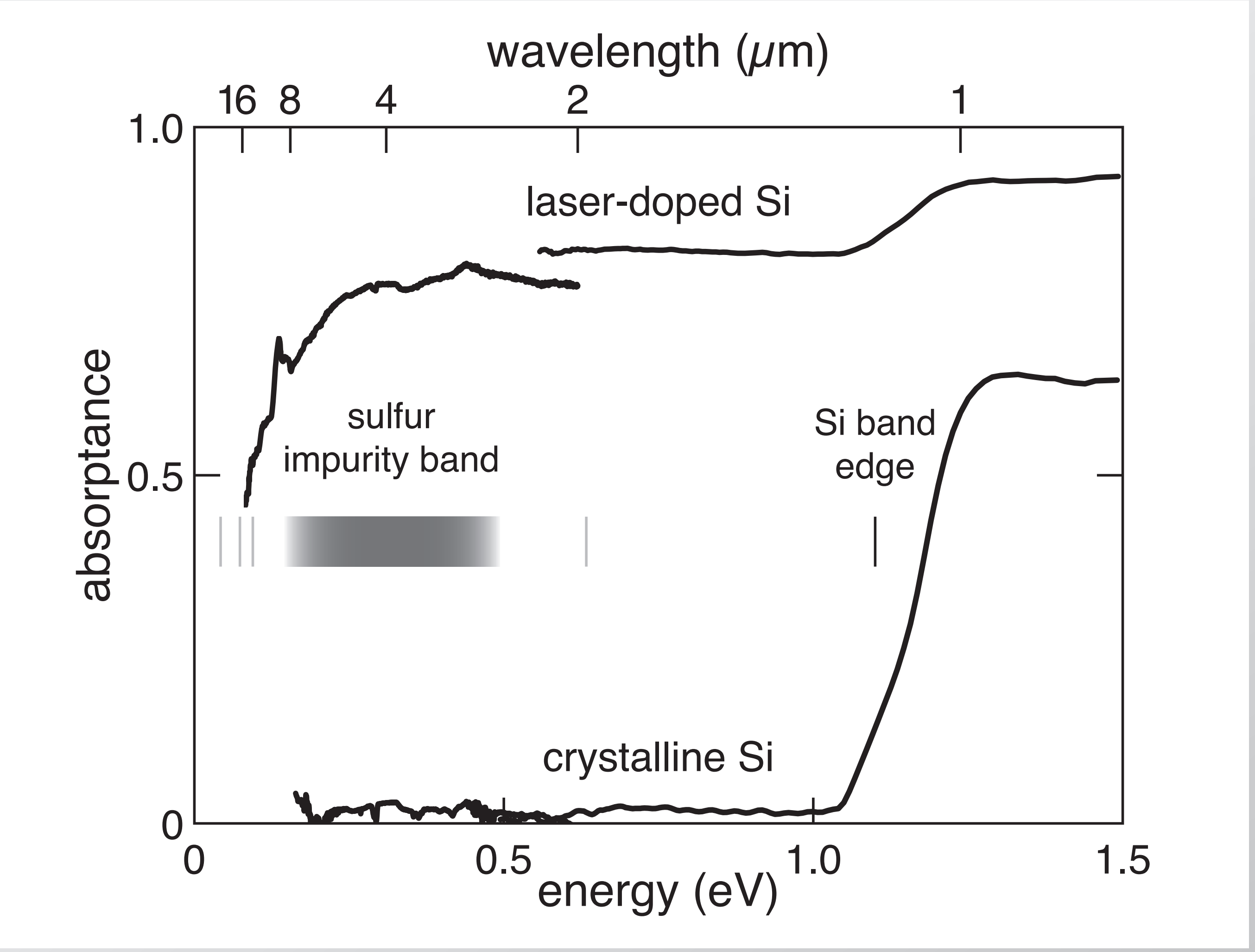
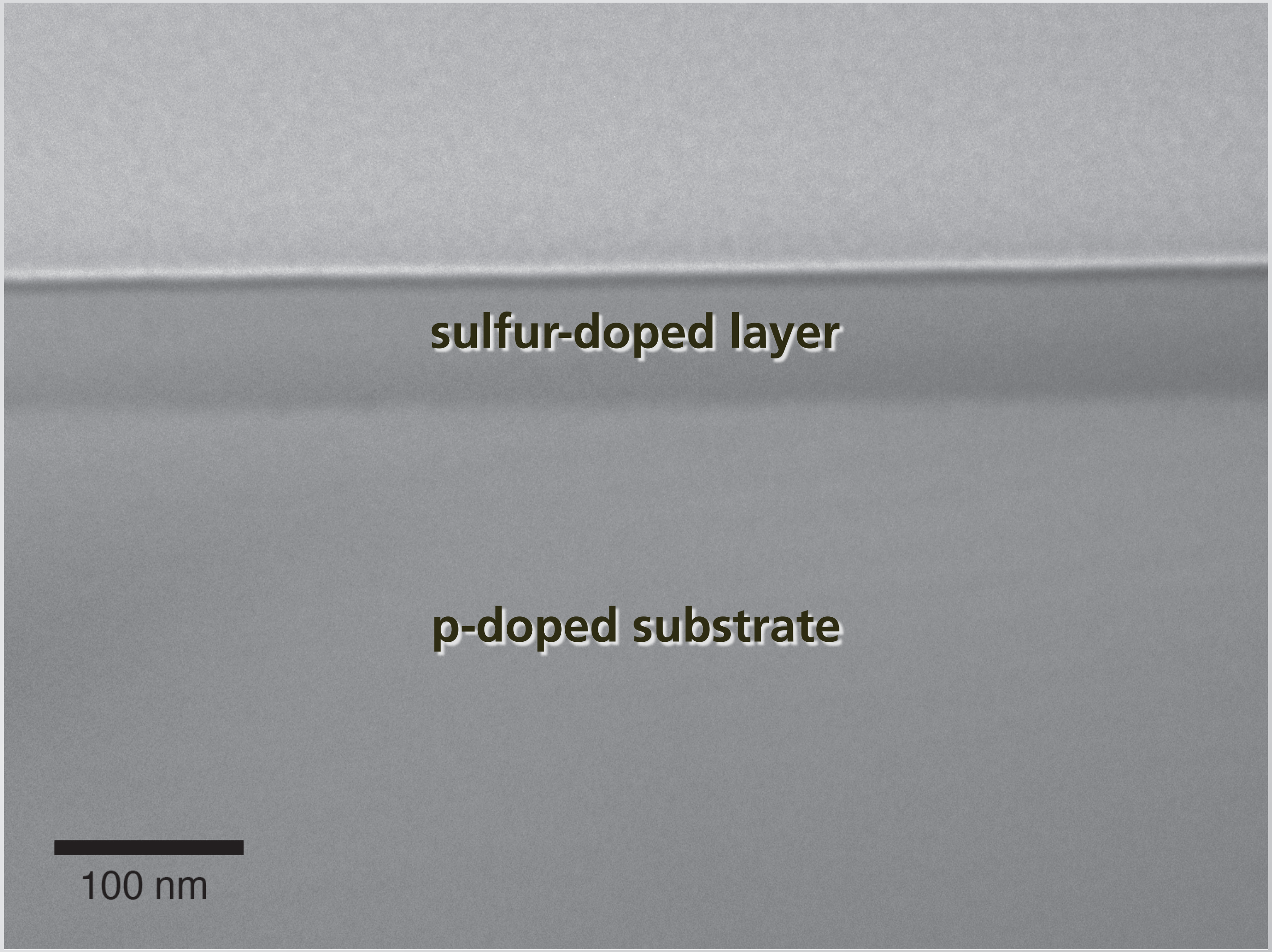


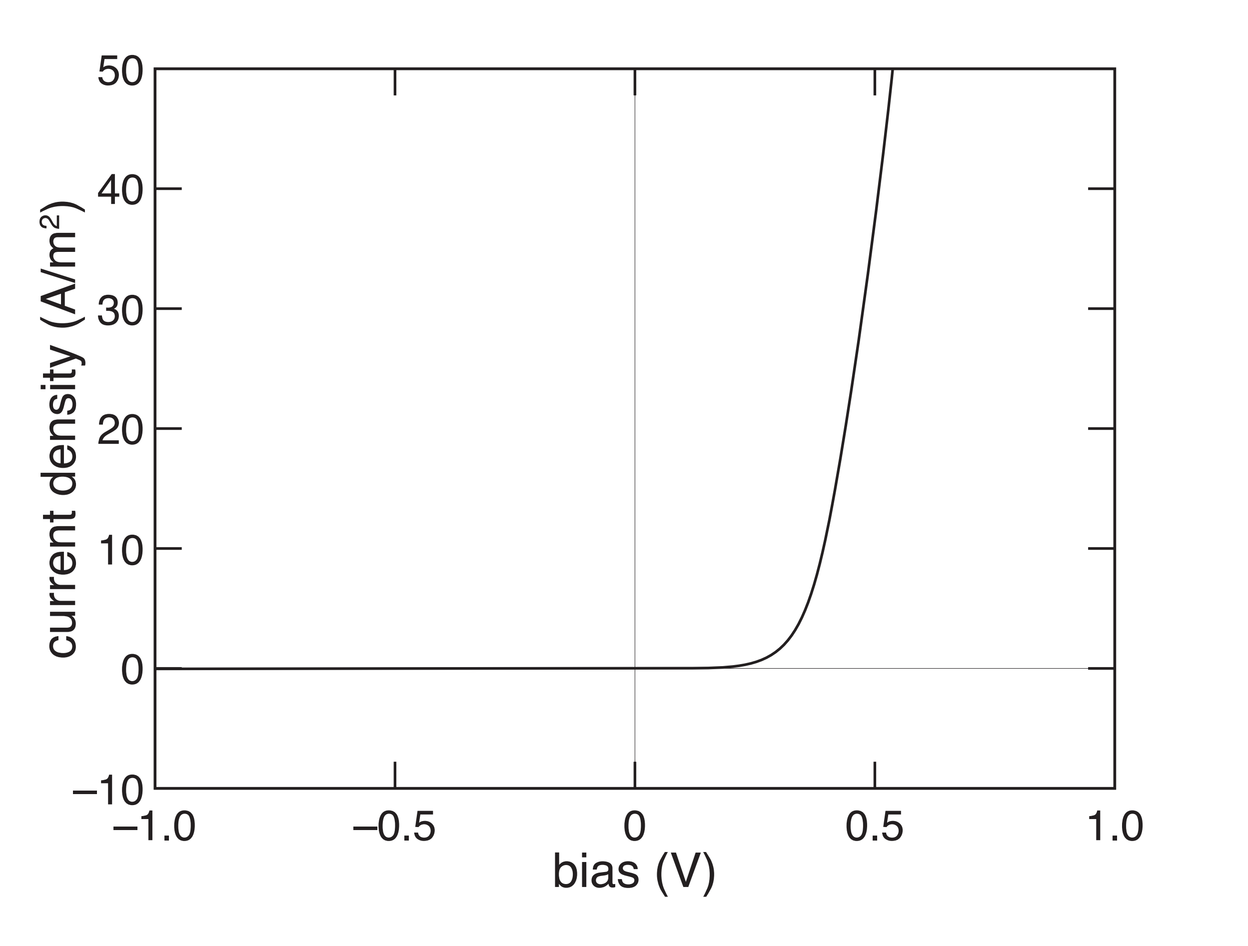
Optoelectronic properties

should have shallow junction below surface



Optoelectronic properties

excellent rectification (after annealing)



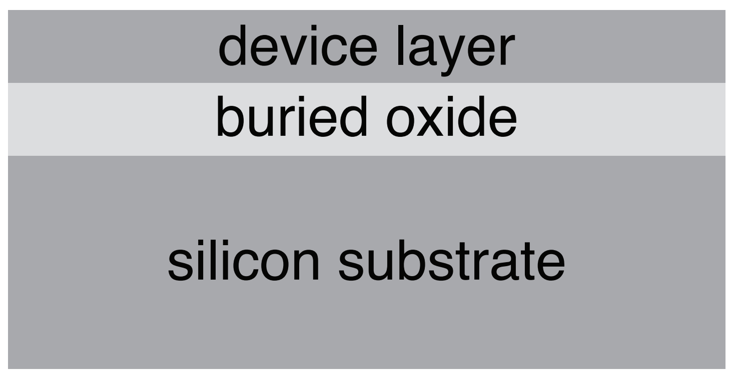
Optoelectronic properties

IV behavior consistent with

impurity band between 200 and 400 meV

Optoelectronic properties

isolate surface layer for Hall measurements



Optoelectronic properties

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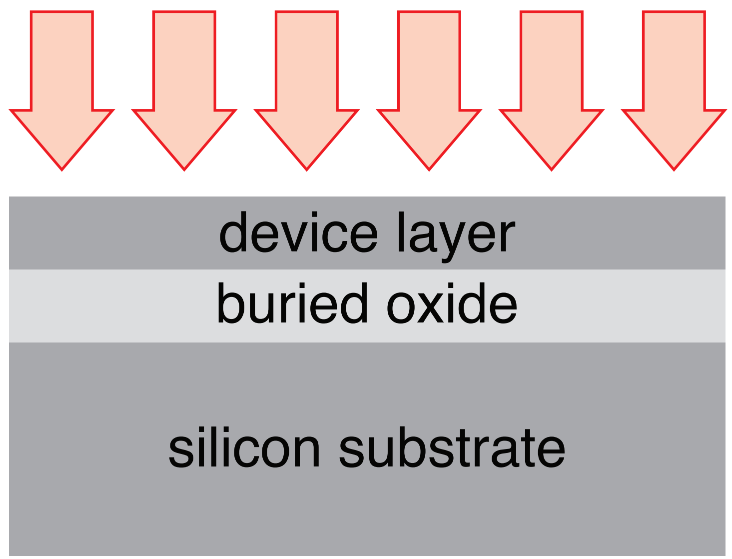

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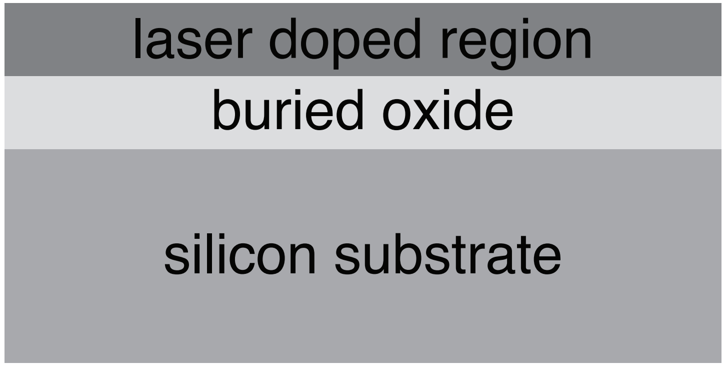
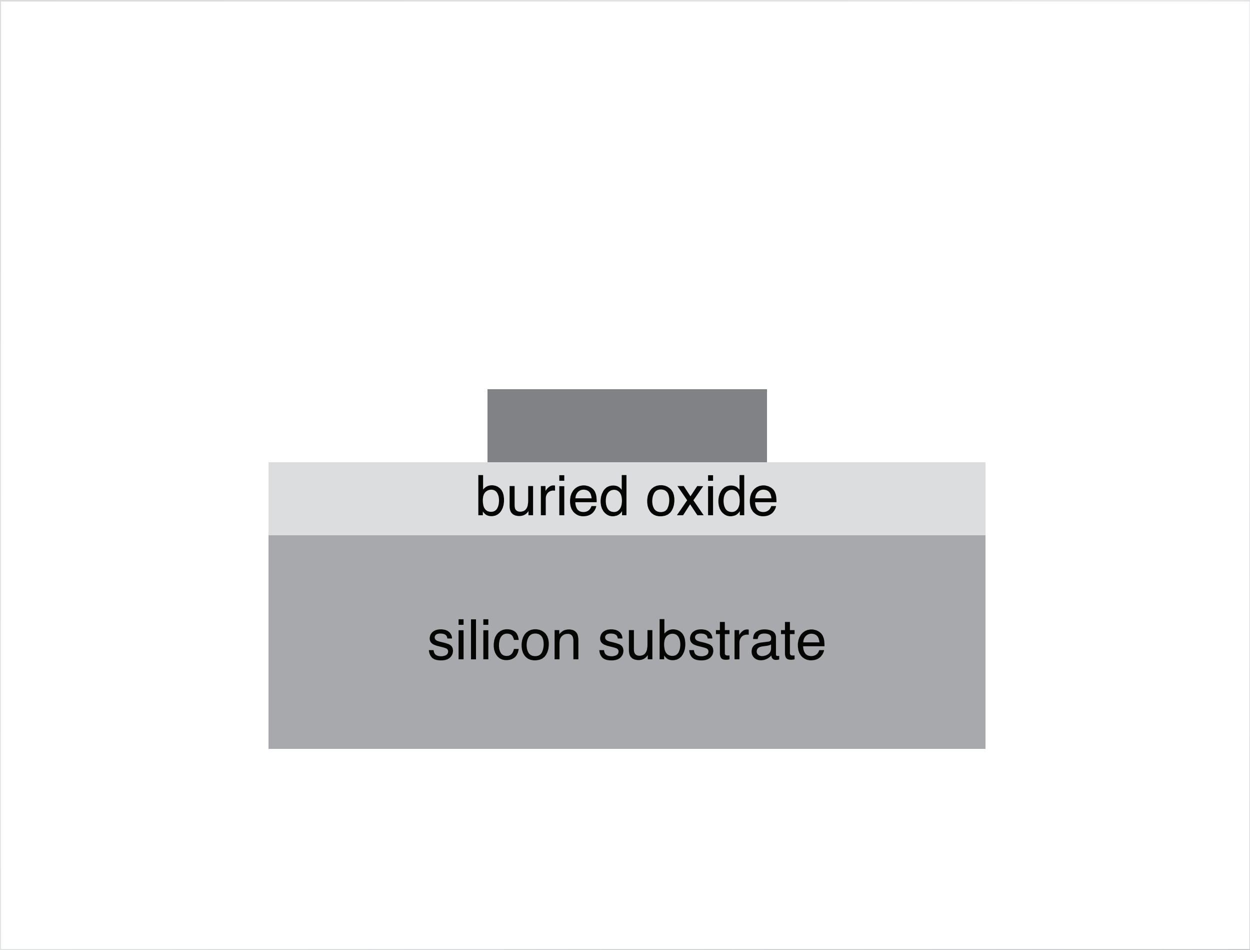


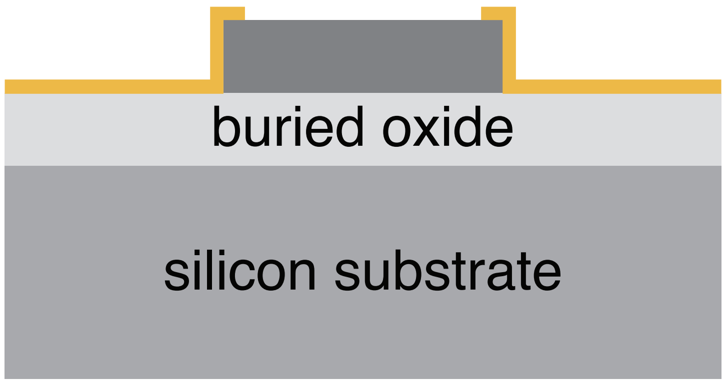
Optoelectronic properties

isolate surface layer for Hall measurements

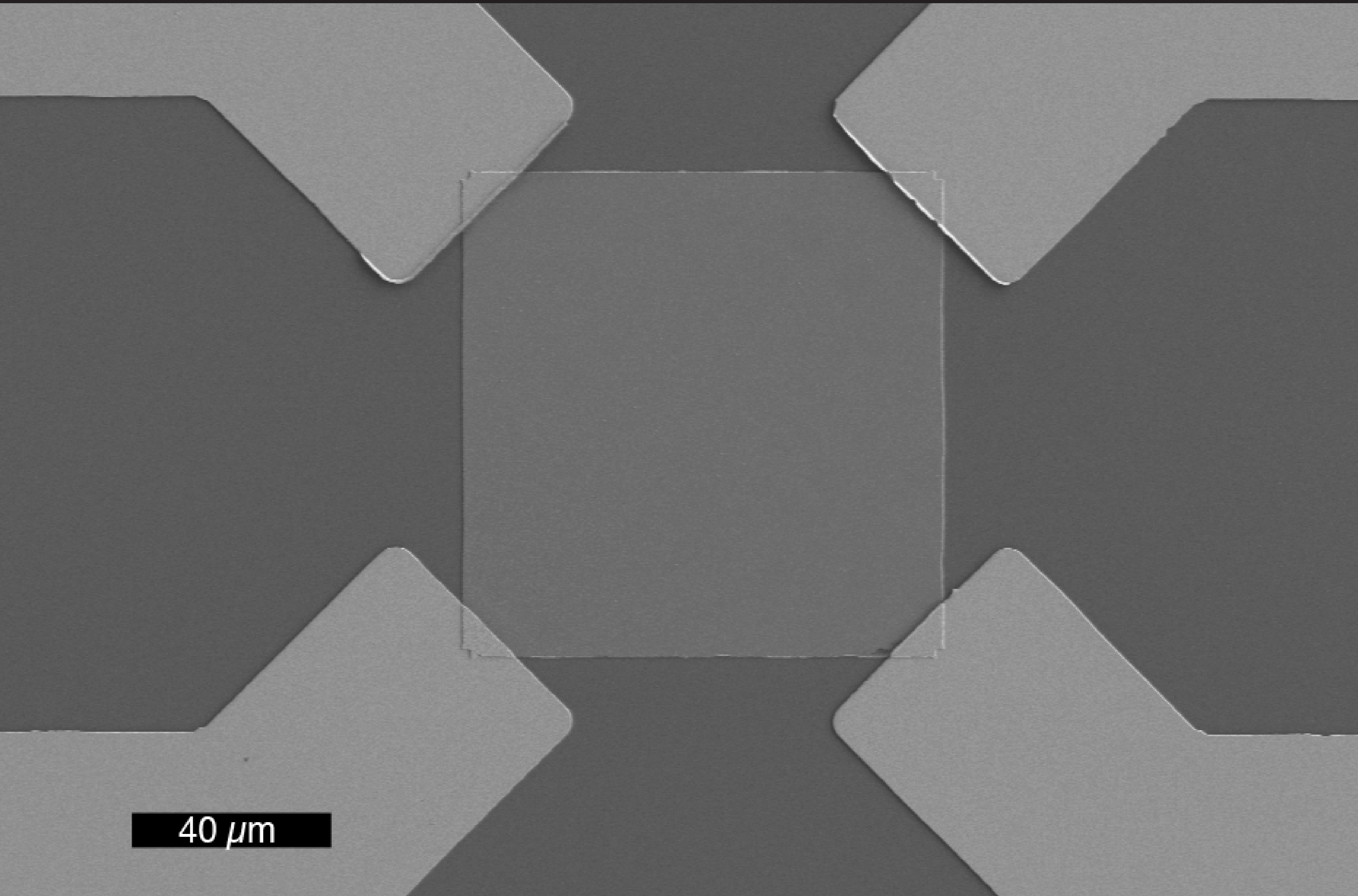


Optoelectronic properties

isolate surface layer for Hall measurements

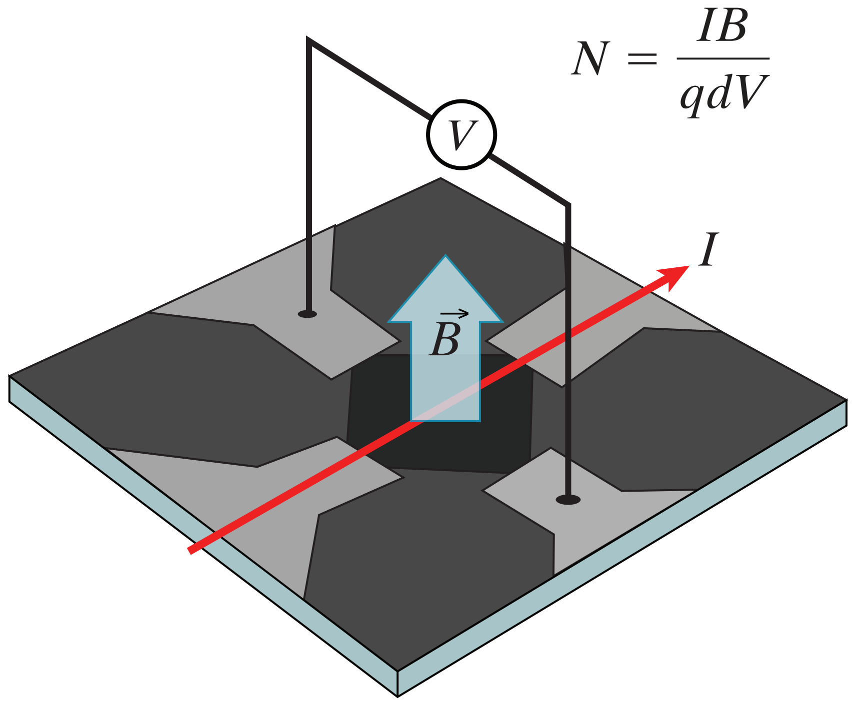


Optoelectronic properties



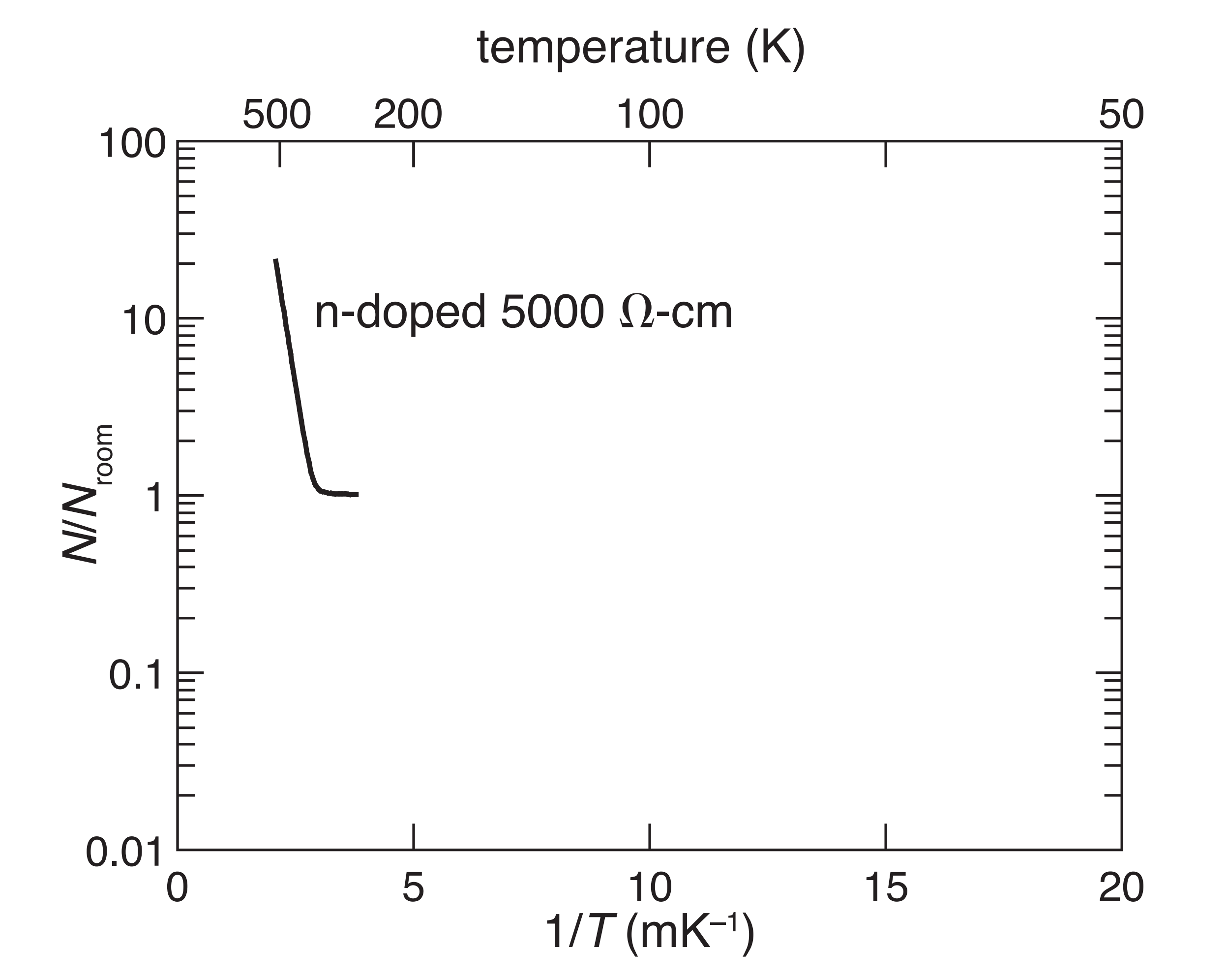
Optoelectronic properties

Hall measurements



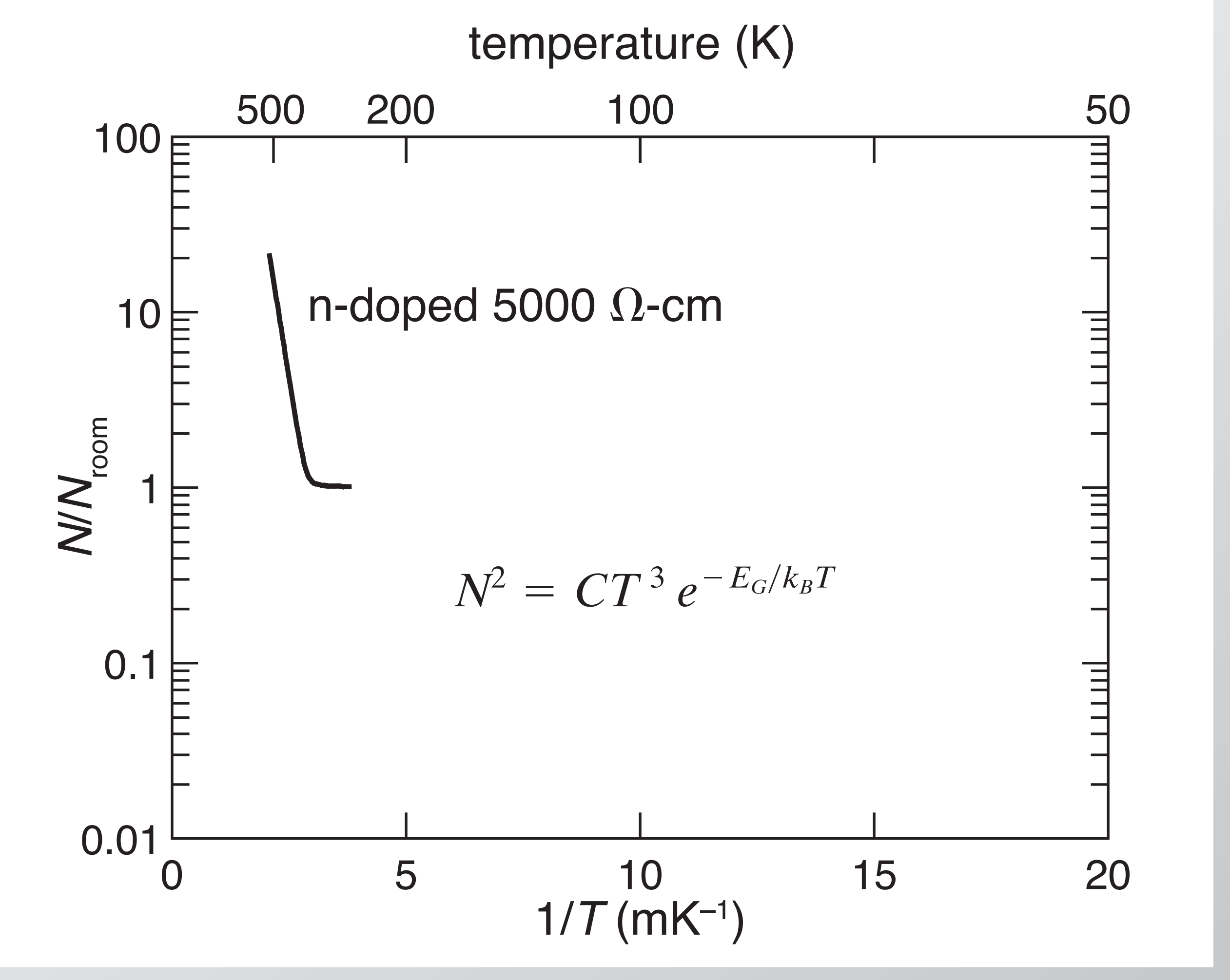
Optoelectronic properties

Hall measurements



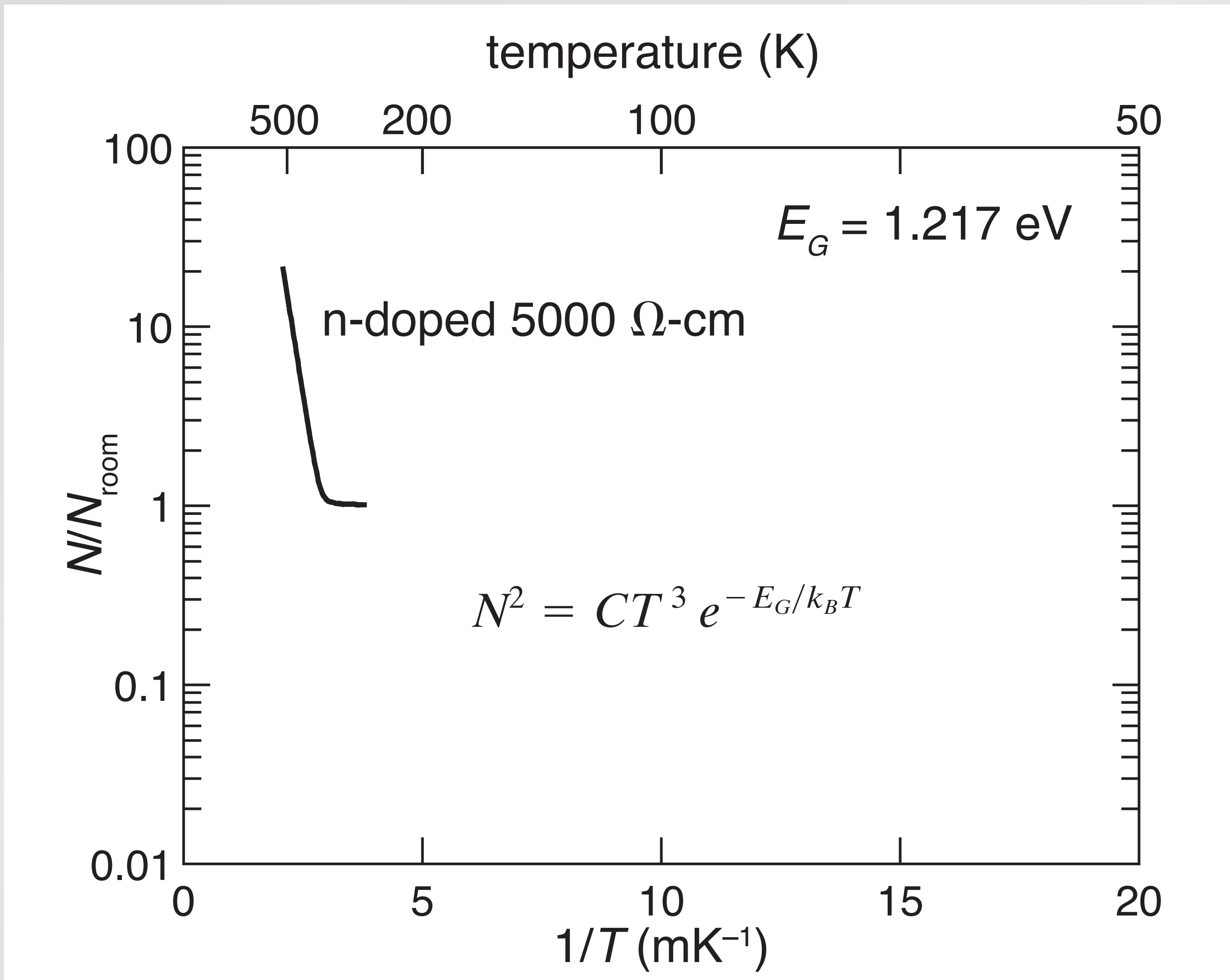
Optoelectronic properties

Hall measurements



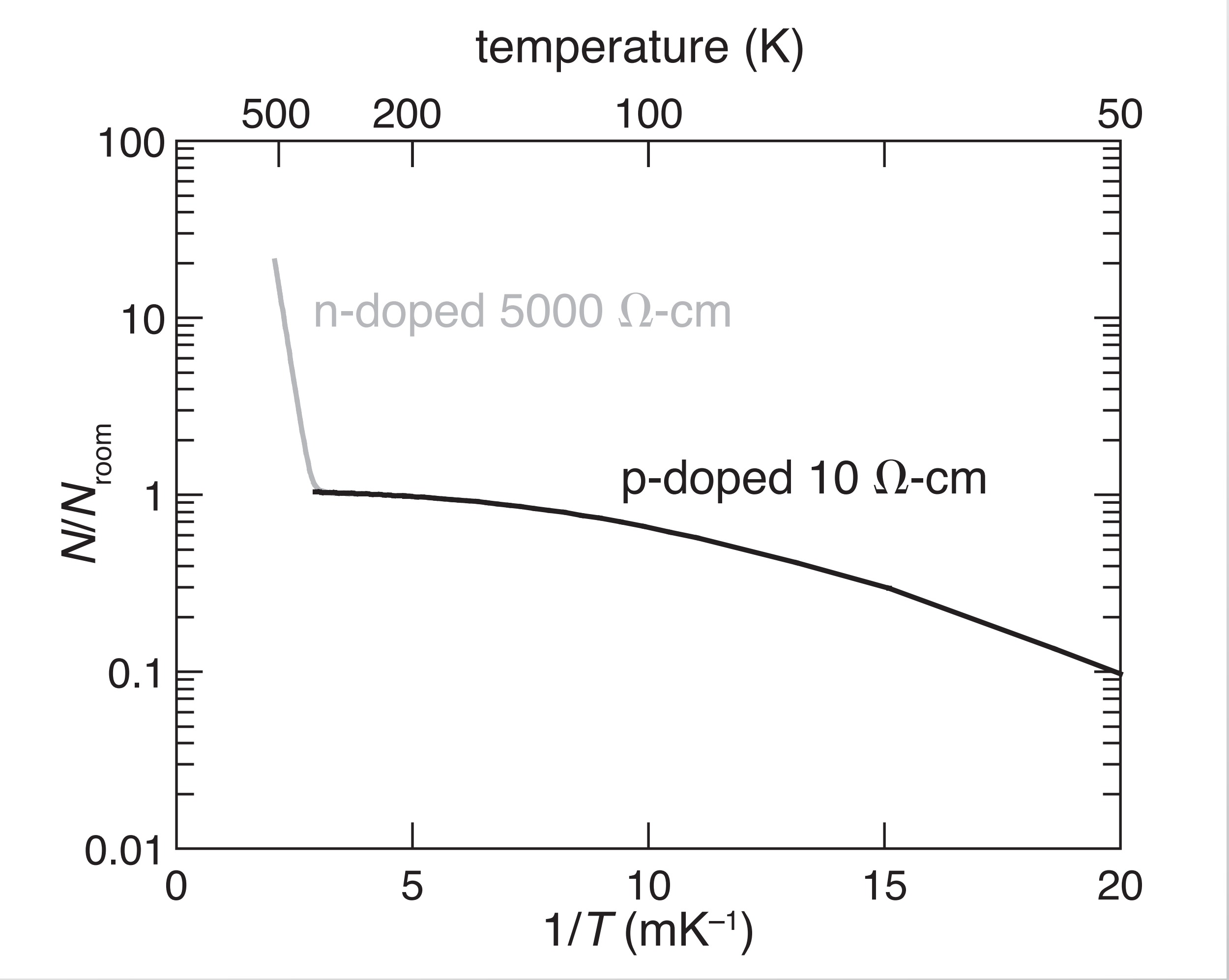
Optoelectronic properties

Hall measurements



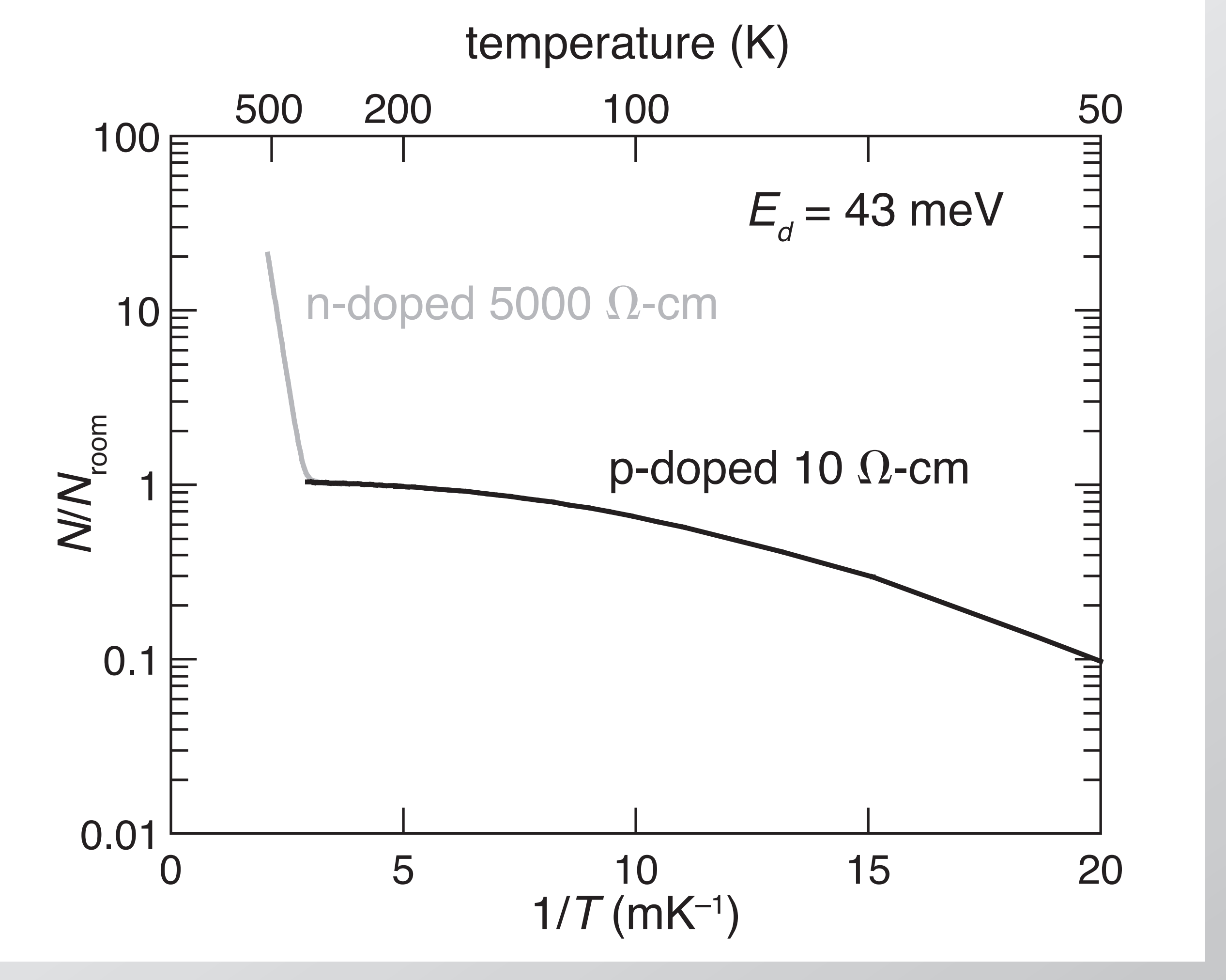
Optoelectronic properties

Hall measurements



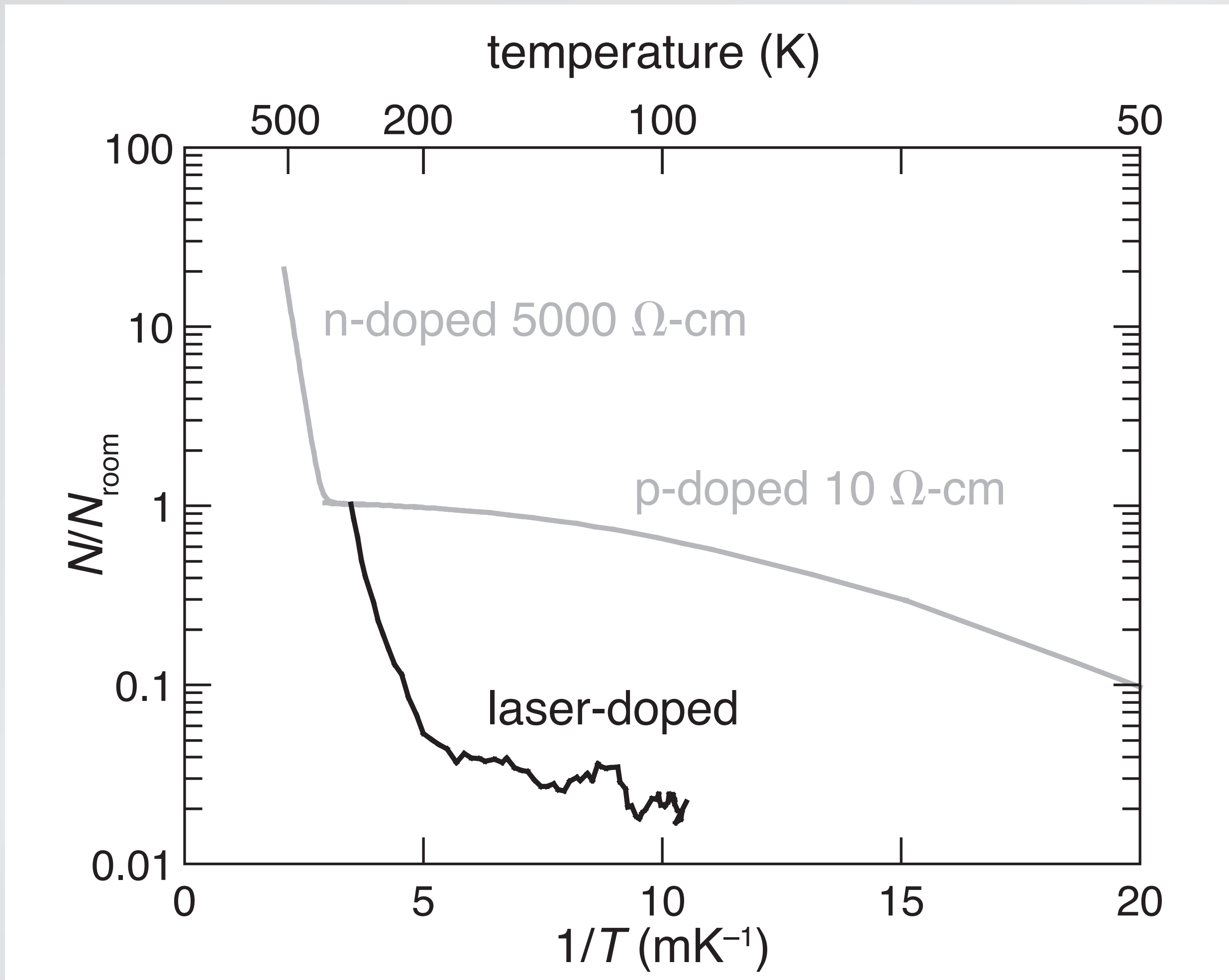
Optoelectronic properties

Hall measurements



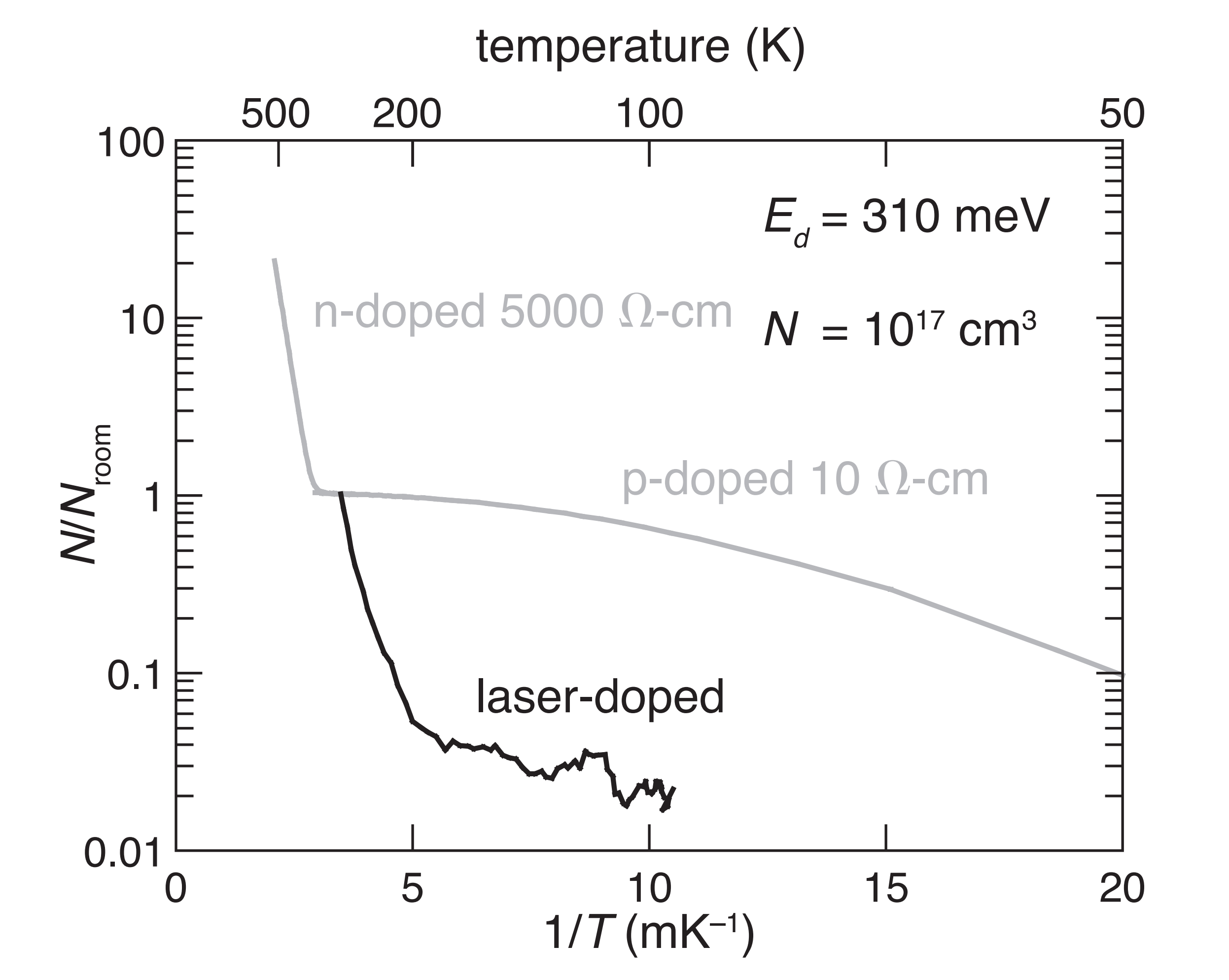
Optoelectronic properties

Hall measurements



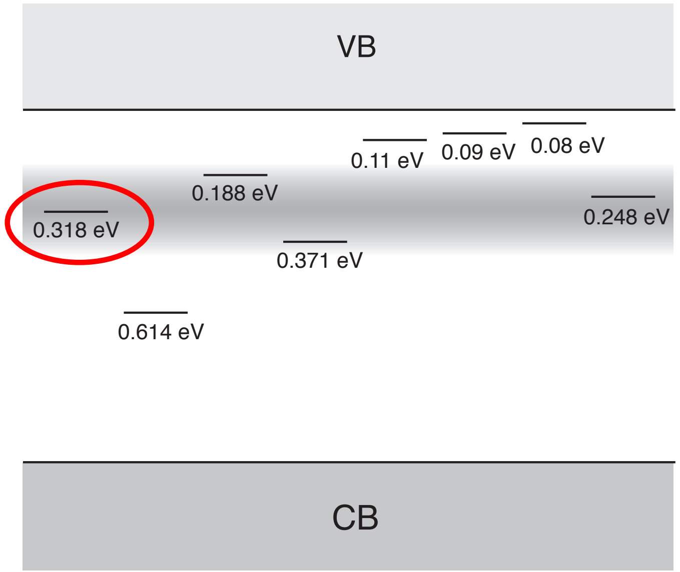
Optoelectronic properties

Hall measurements



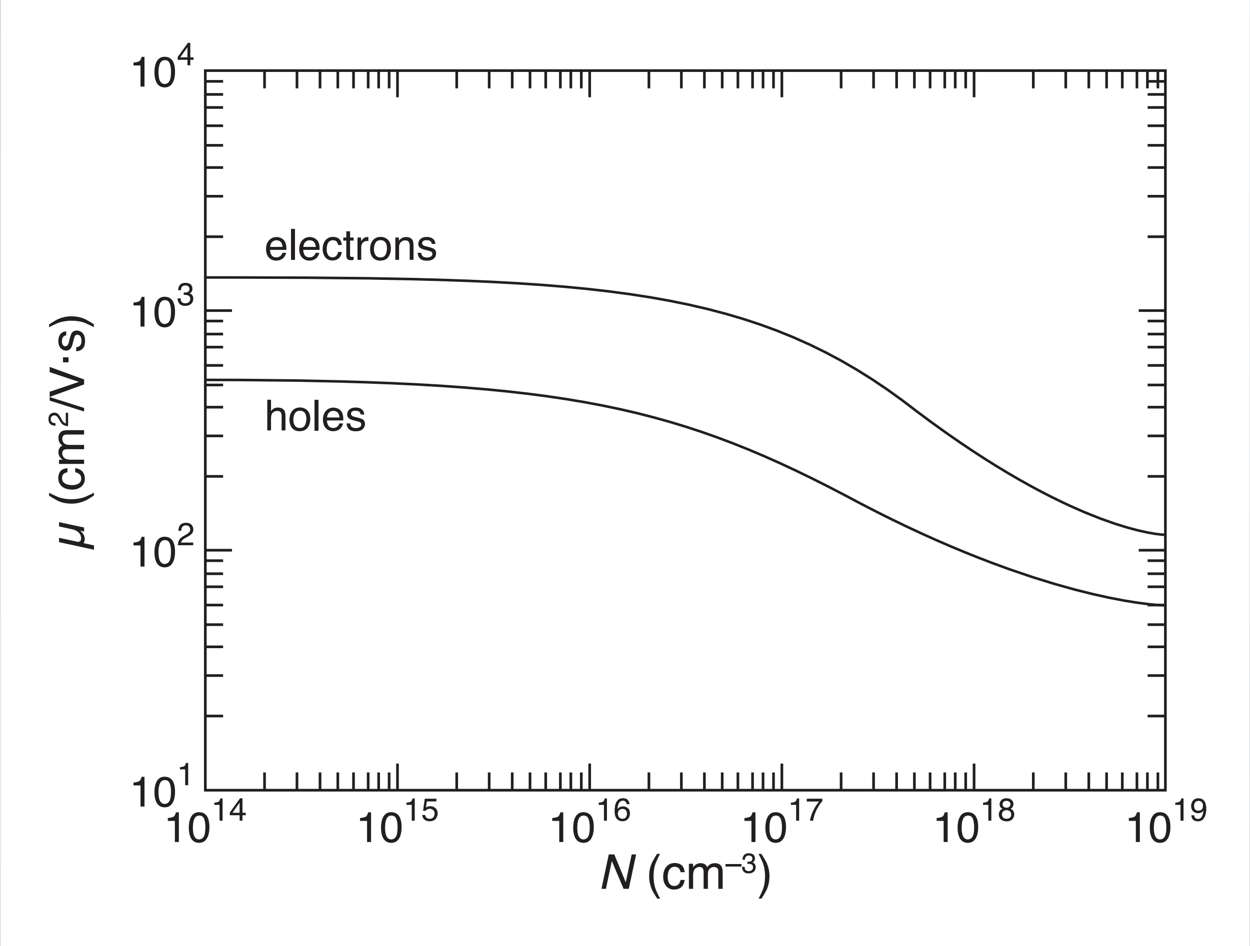
Optoelectronic properties

impurity (donor) band centered at 310 meV



Optoelectronic properties

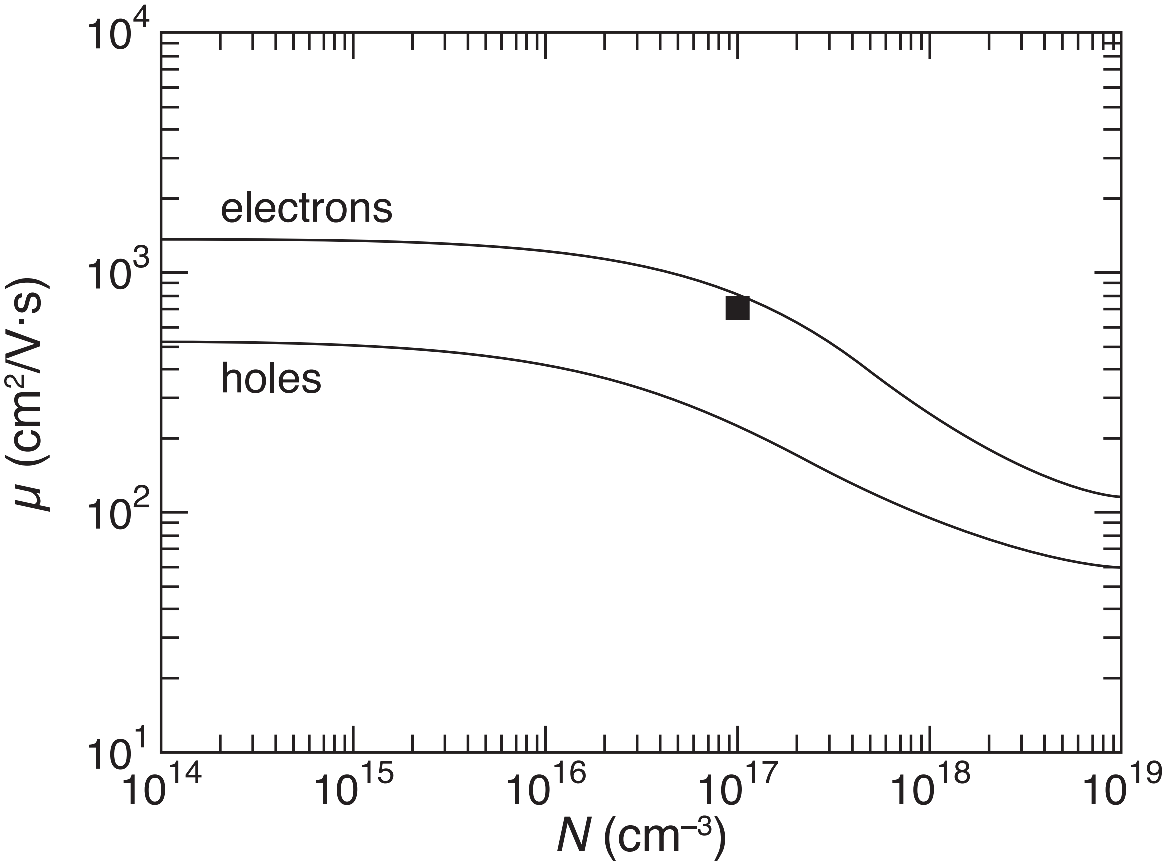
majority carrier mobility



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

Optoelectronic properties

majority carrier mobility



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

Optoelectronic properties

Things to keep in mind

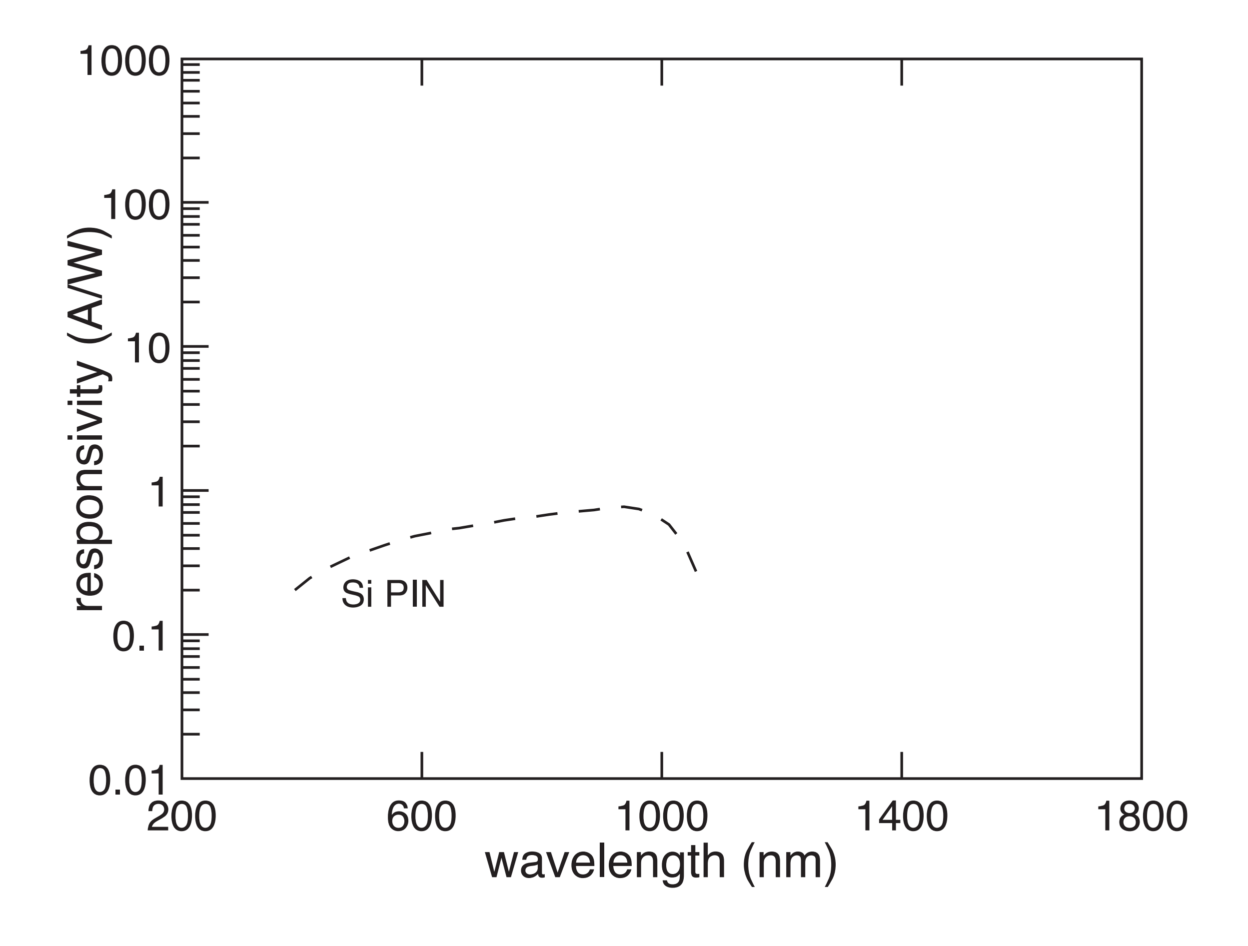
- IR absorption rolls off around 8 µm
- 1 in 10^3 sulfur atoms are ionized donors at 300 K
- all data indicate these S donors are substitutional

Outline

- structure
- optoelectronic properties
- devices

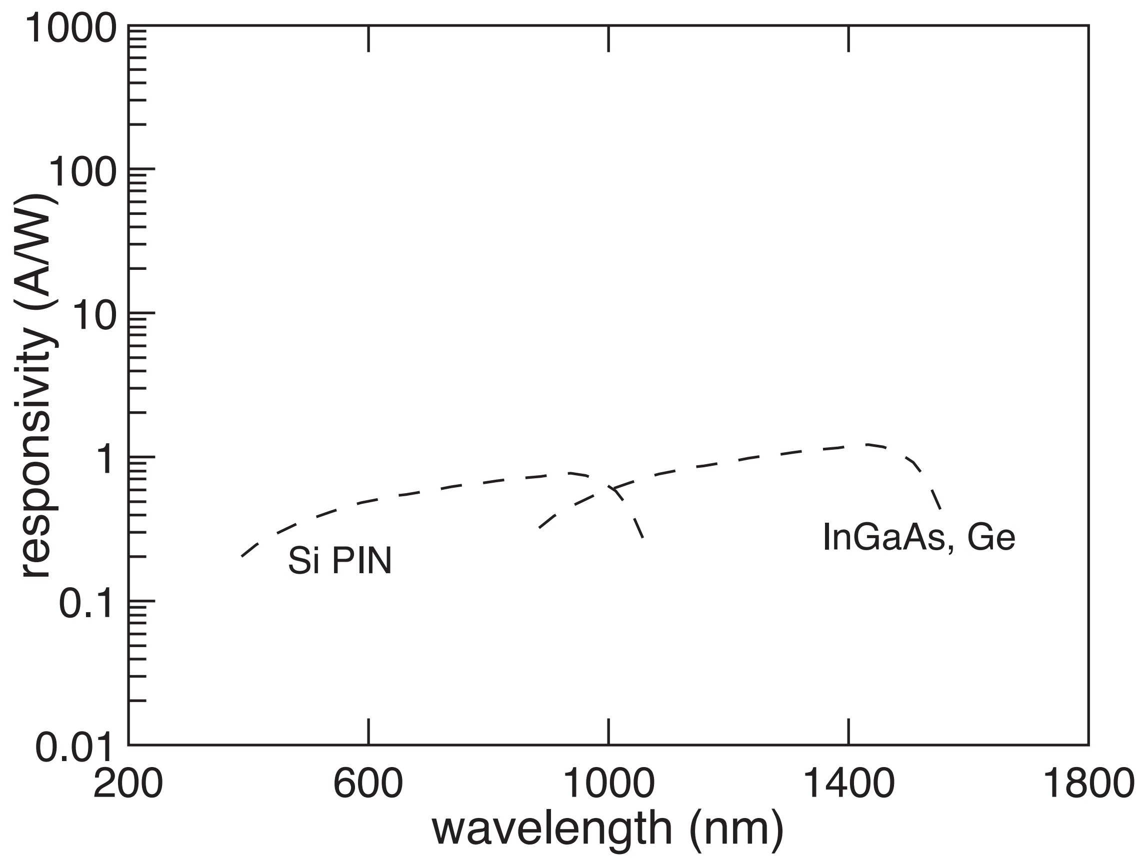
Devices

responsivity



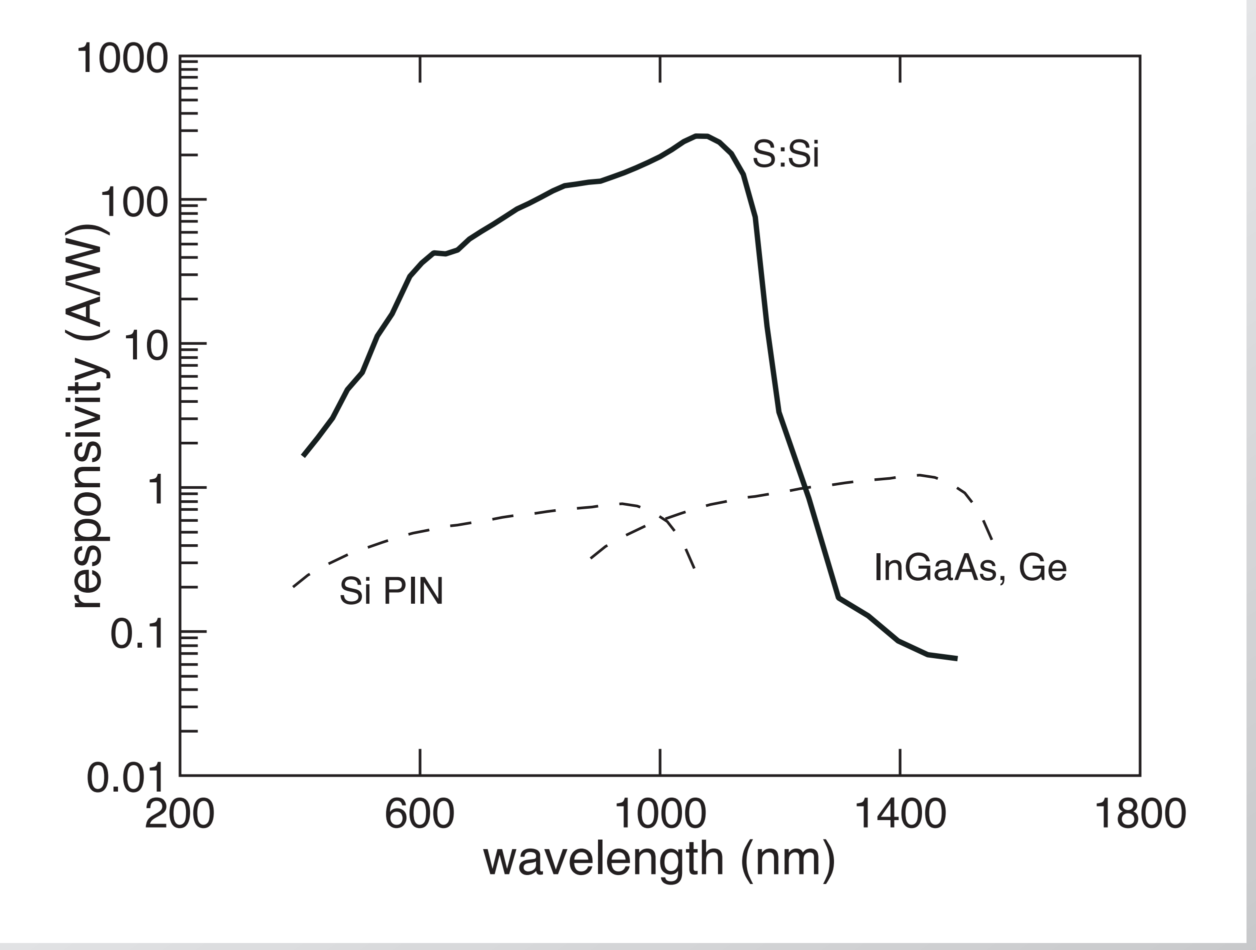
Devices

responsivity



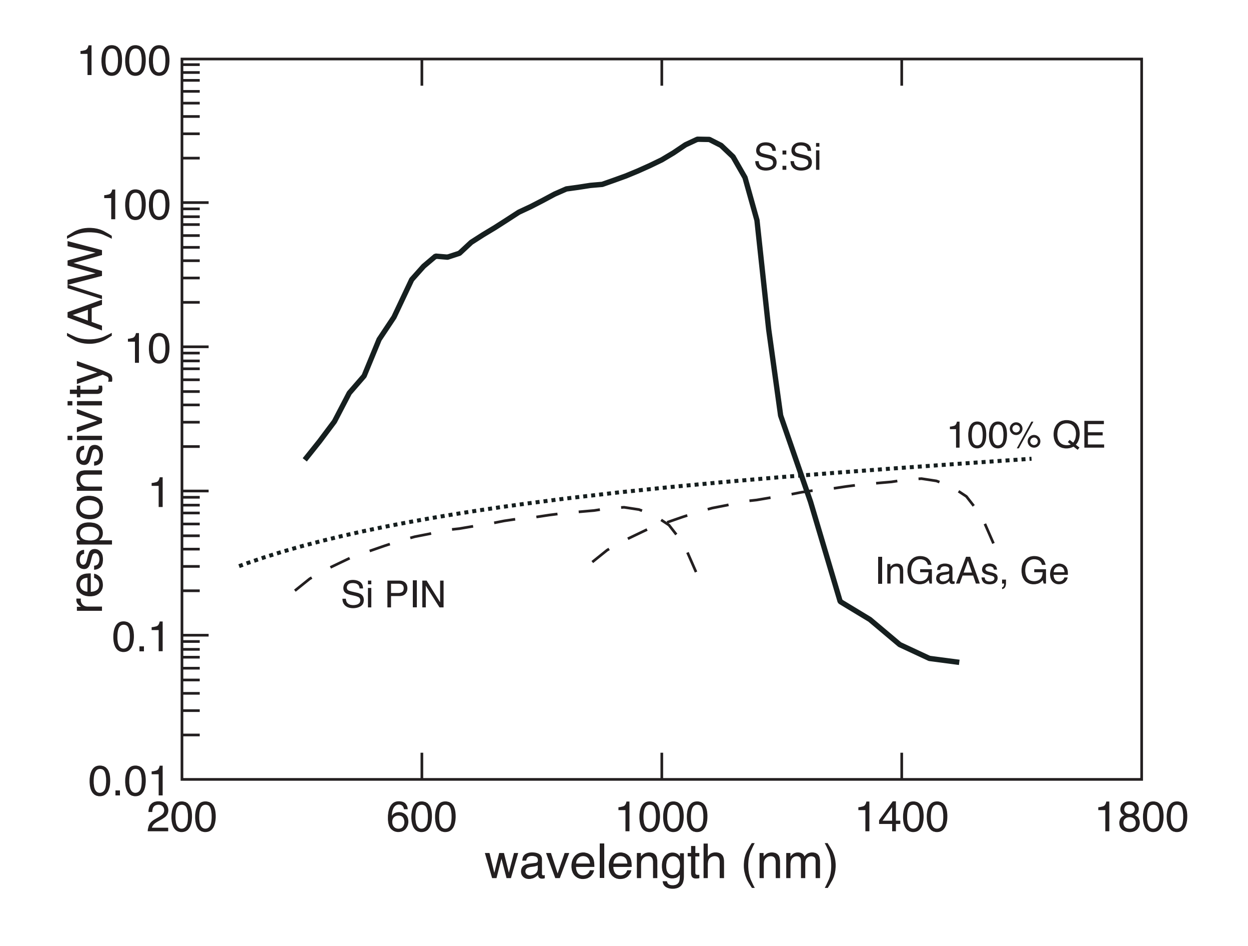
Devices

responsivity



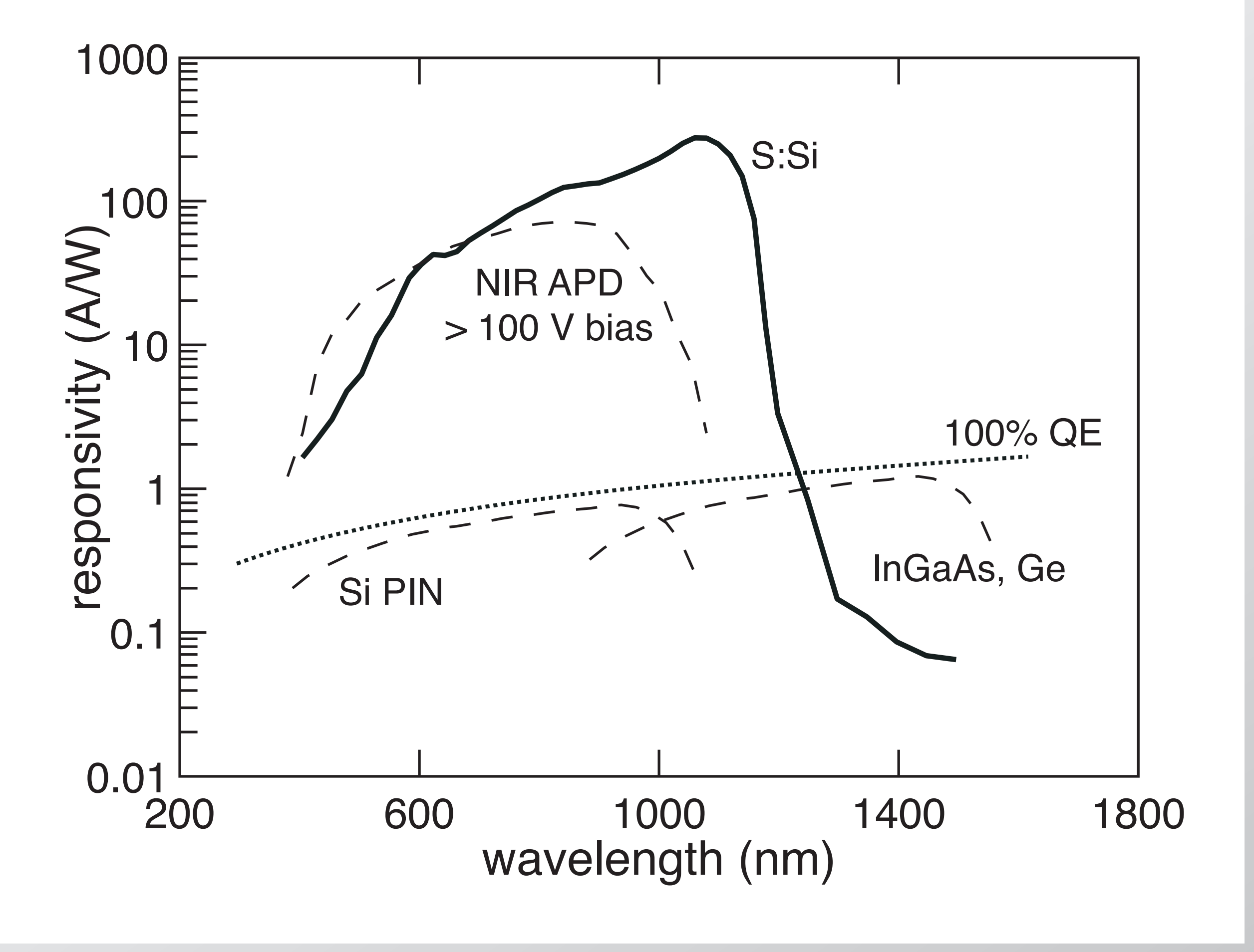
Devices

responsivity



Devices

responsivity



Devices

What causes gain?

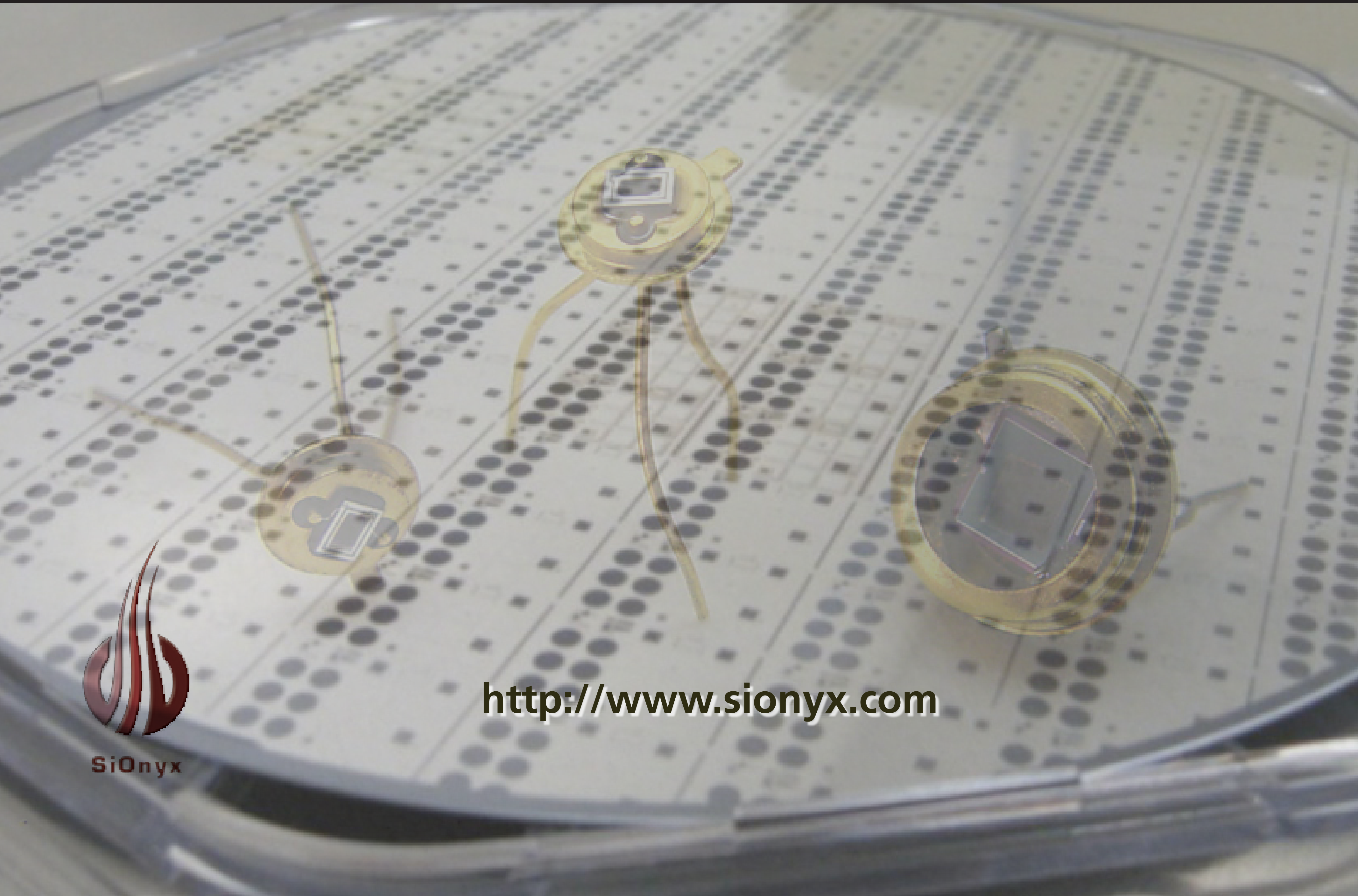
- impact excitation (avalanching)
- carrier lifetime >> transit time (photoconductive gain)
- some other mechanism

Devices

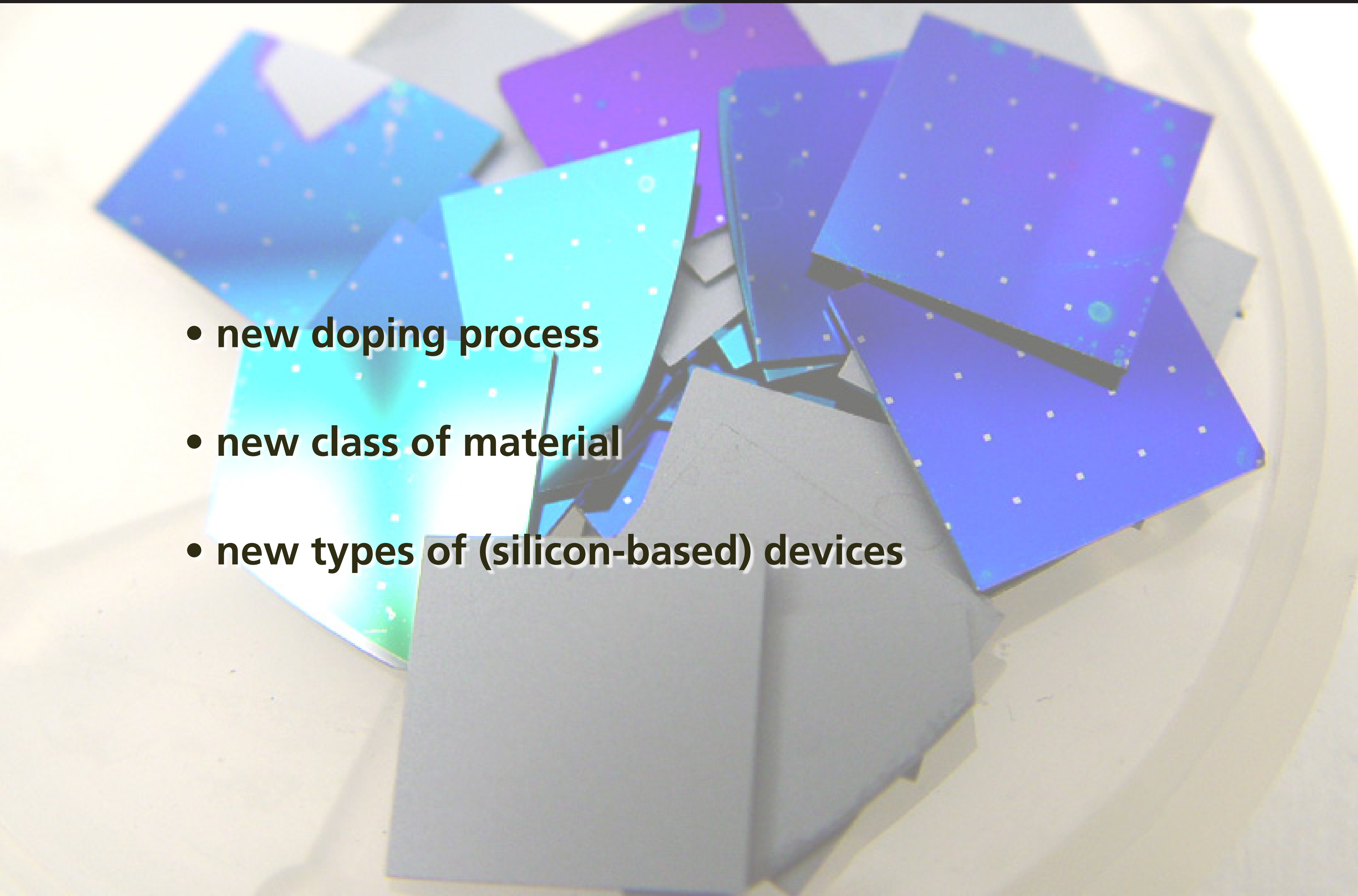
Things to keep in mind

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

Devices

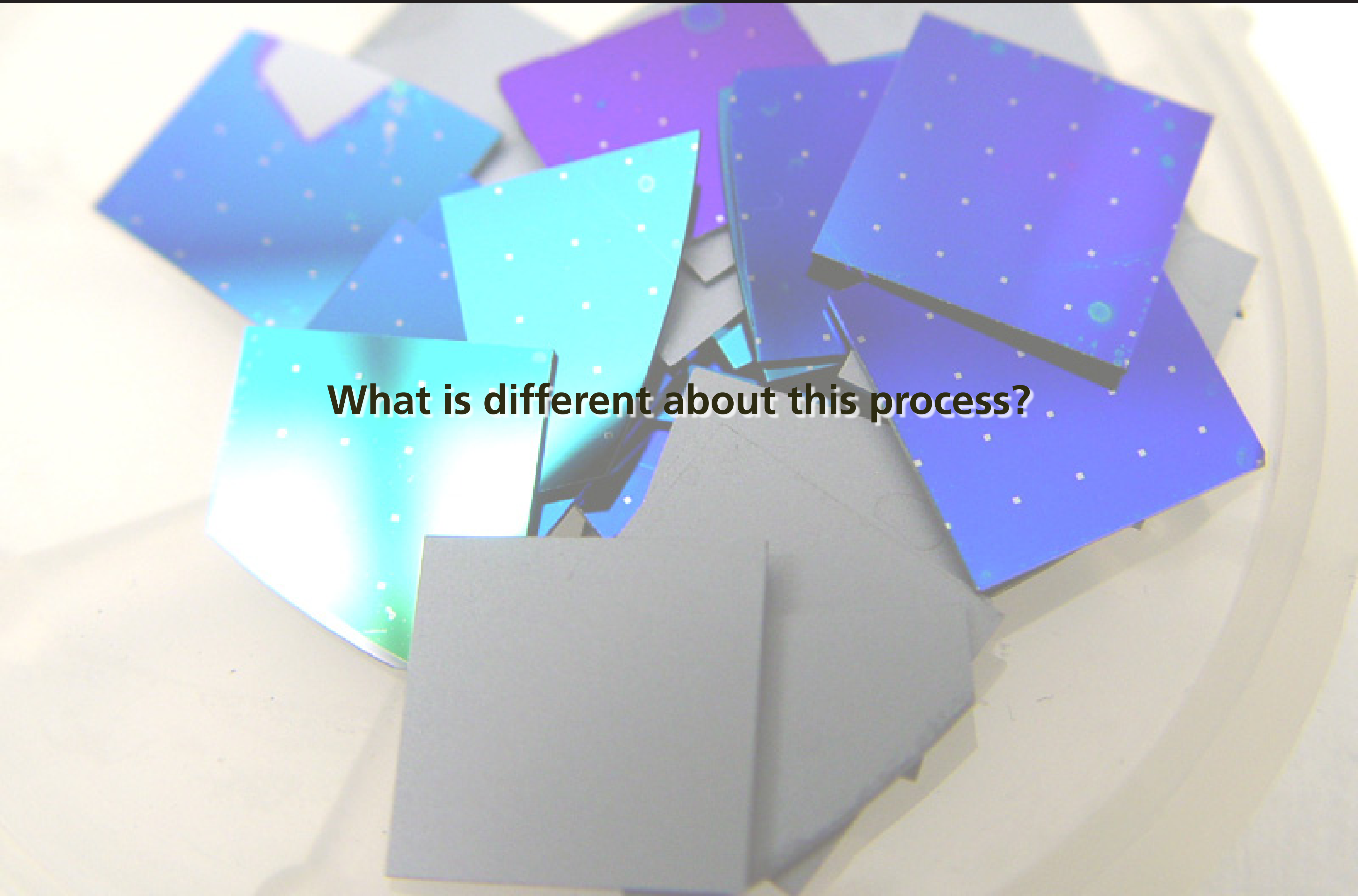


Conclusion



- 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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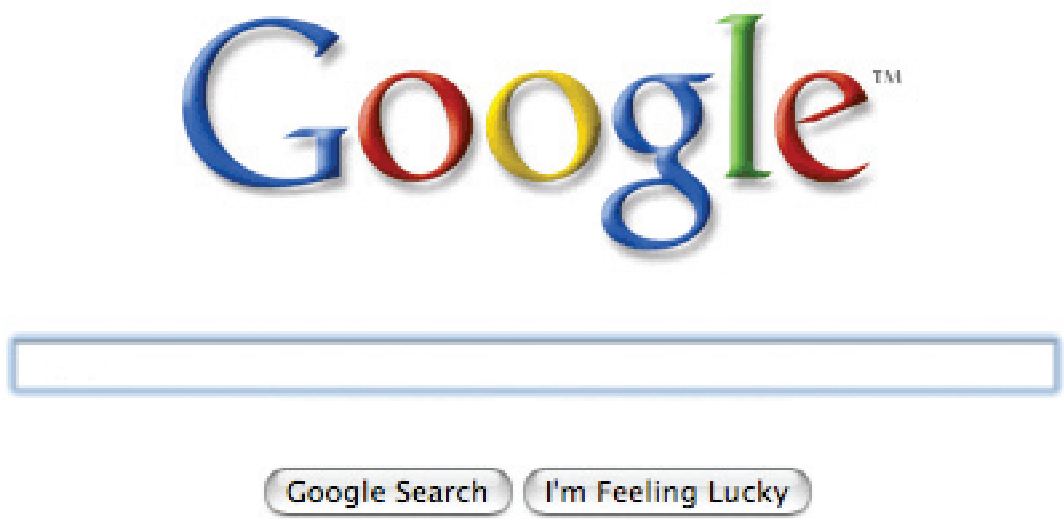
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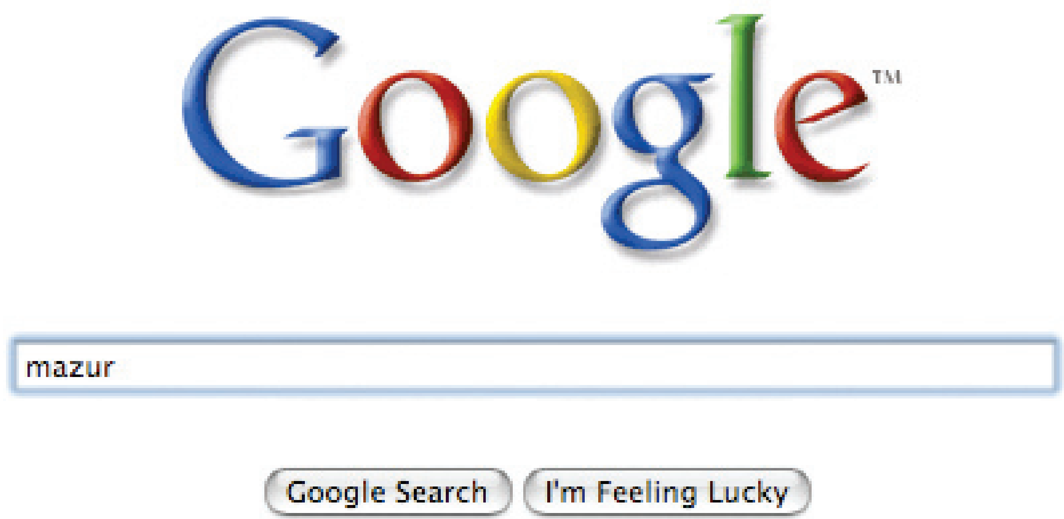
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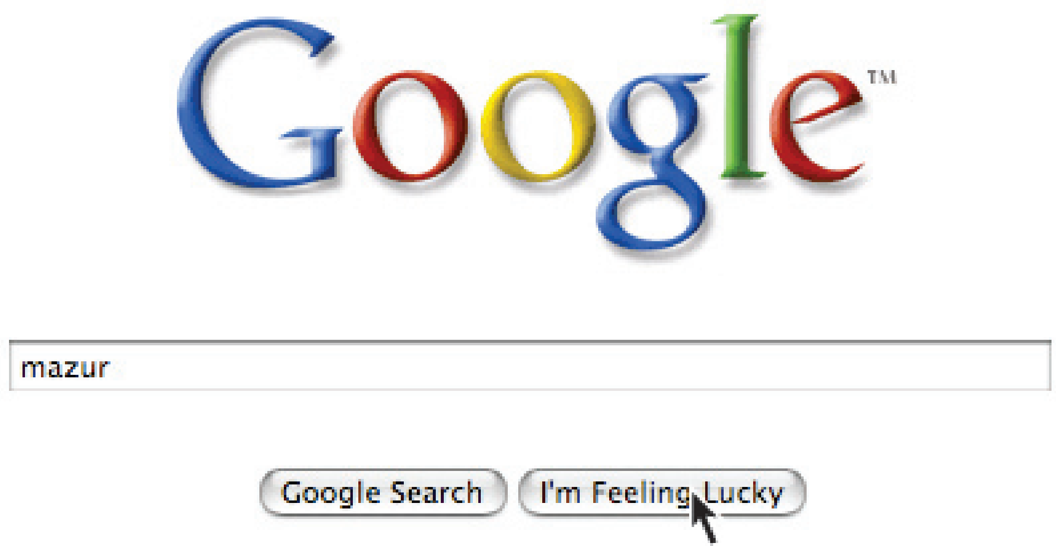
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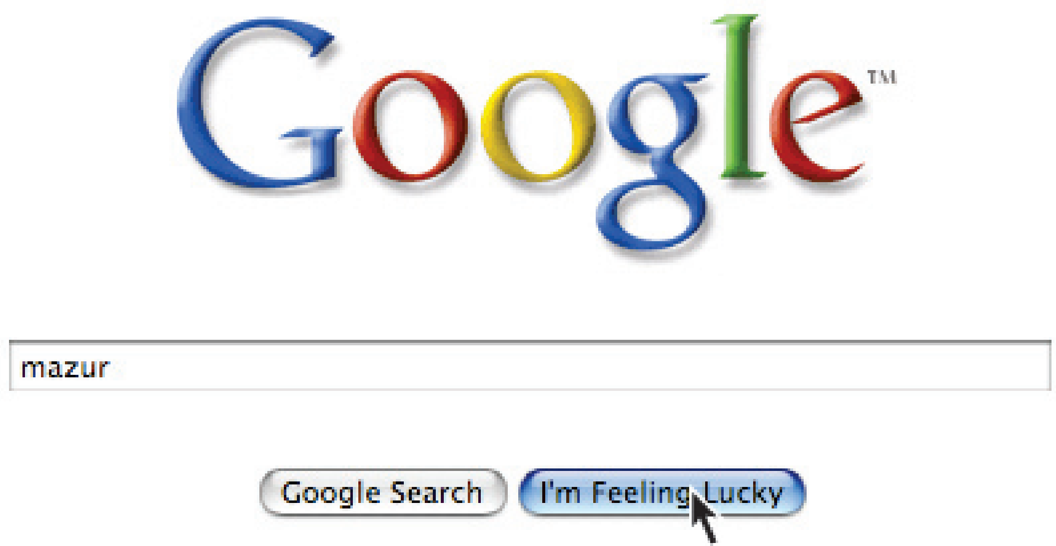
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