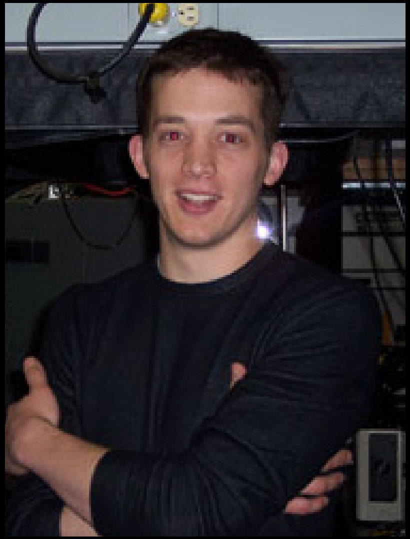
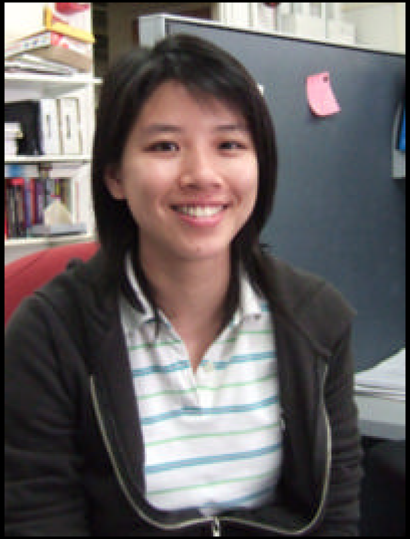
Black silicon briefing

Night Vision Perspectives on Technology
Night Vision & Electronic Sensors Directorate
Ft. Belvoir, VA, 26 May 2009


Mark Winkler


Renee Sher


Yu-Ting Lin


Eric Mazur

and also....

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

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)

Prof. Augustinus Asenbaum (Vienna)

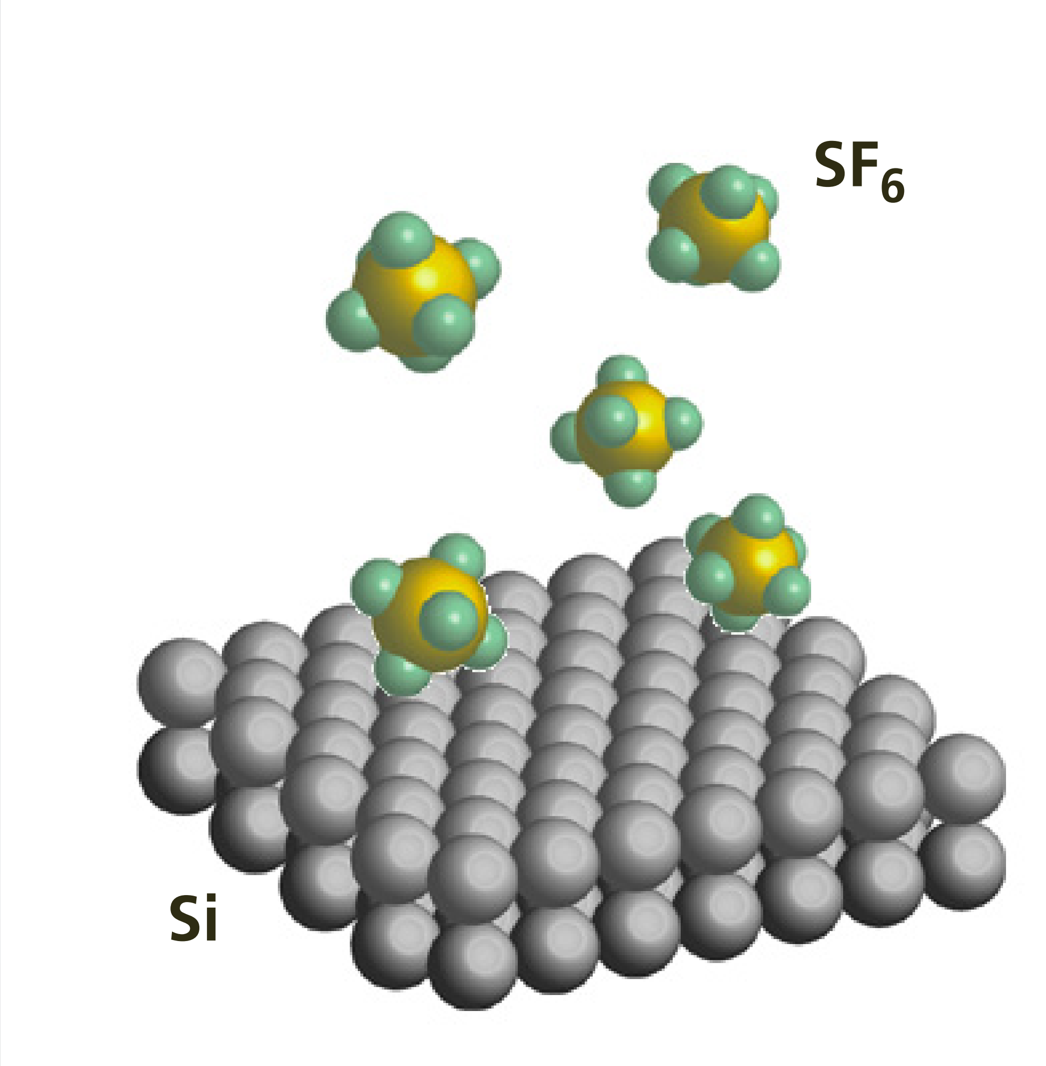
Dr. François Génin (LLNL)
Mark Wall (LLNL)

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

Dr. Pat Maloney (NVSED)

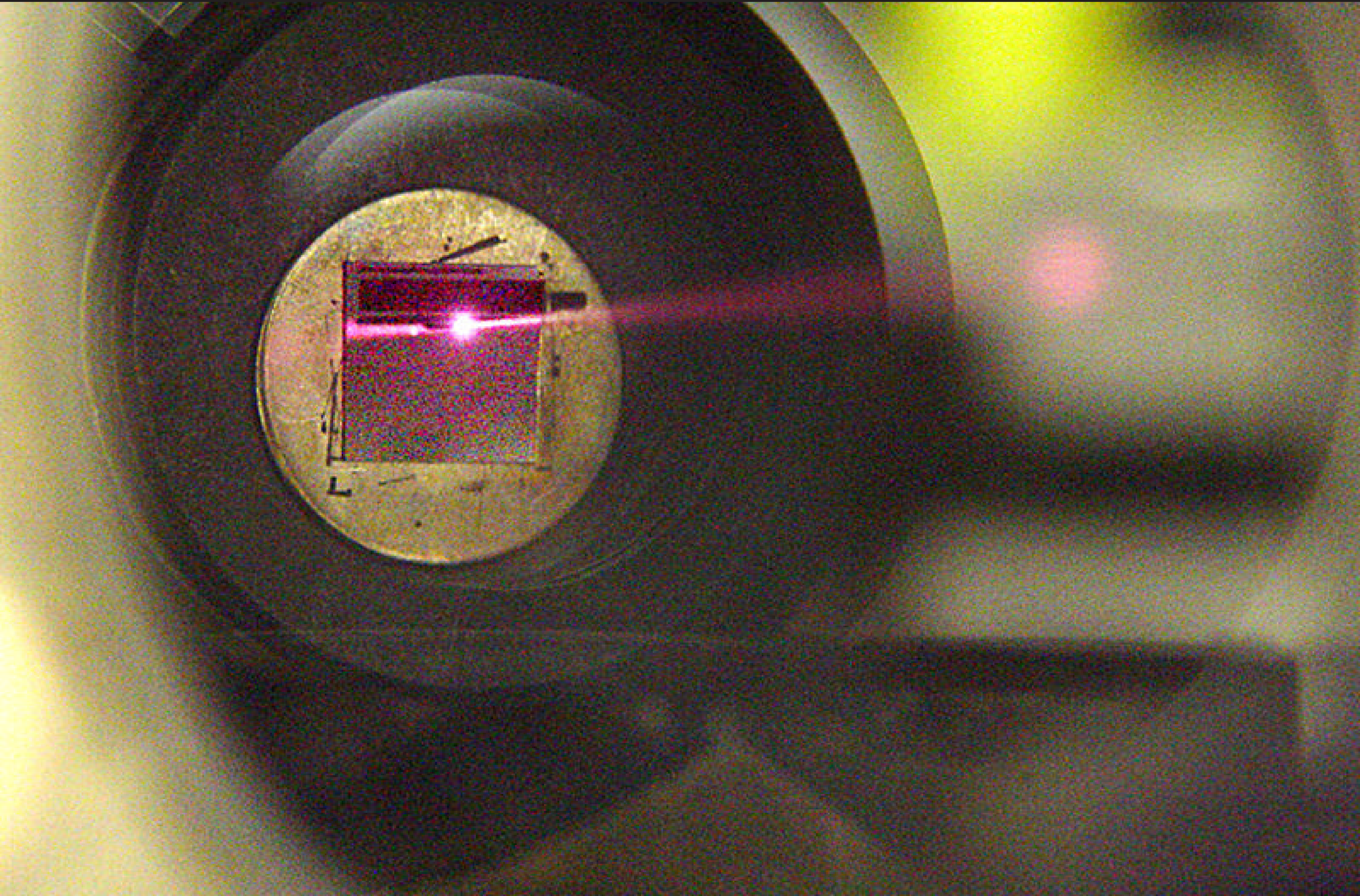
Dr. Jeffrey Warrander (ARDEC)

Introduction



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

Introduction



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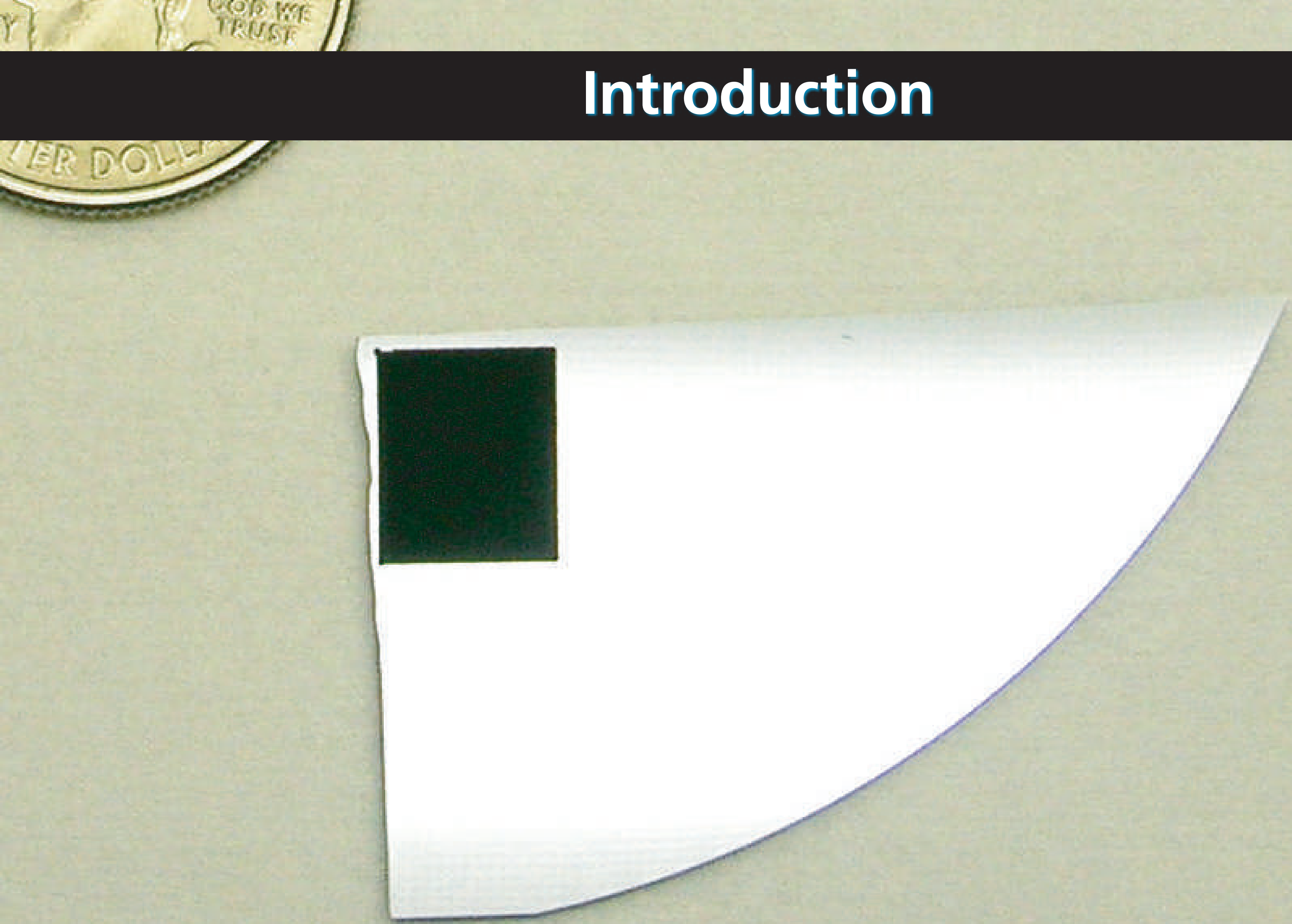
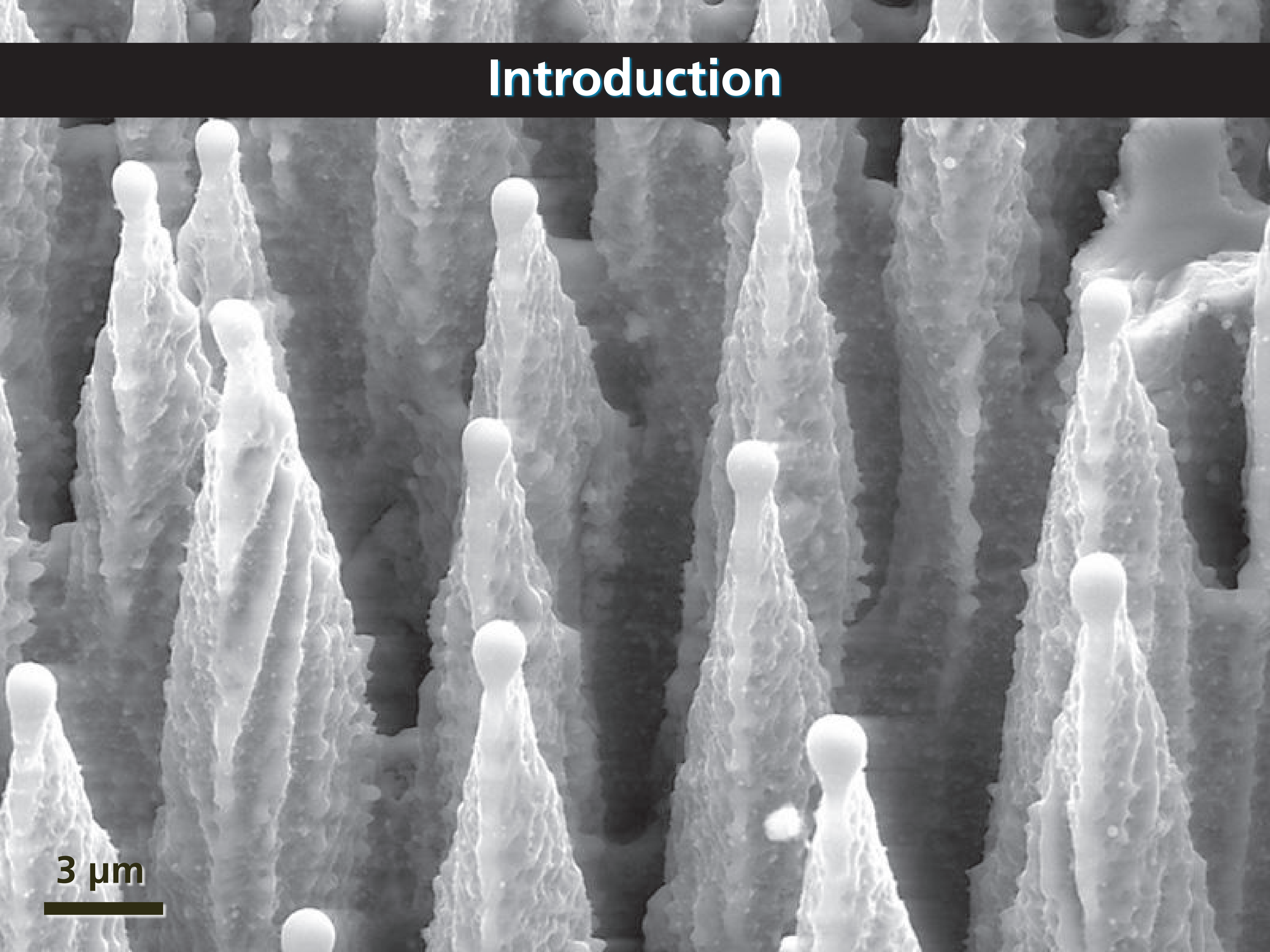


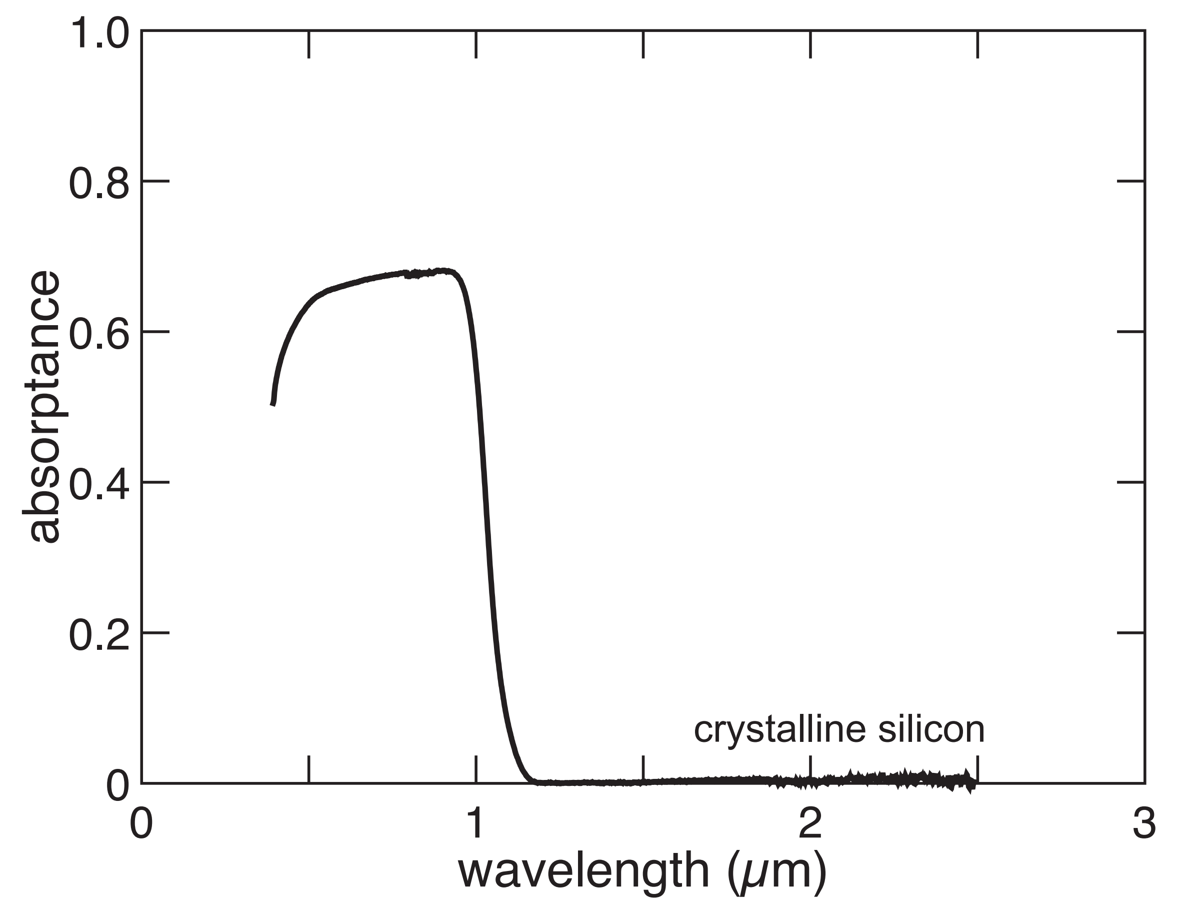
“black silicon”

Introduction



Introduction

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



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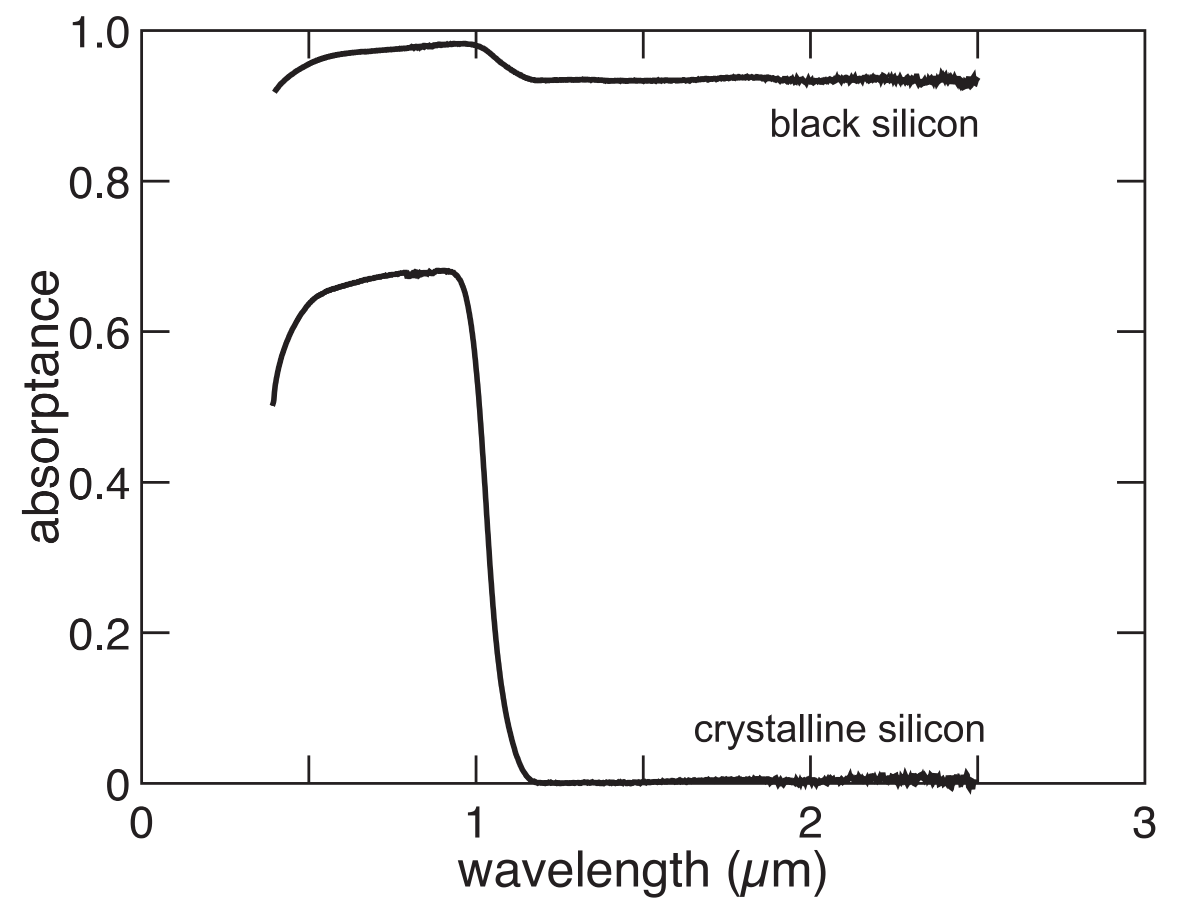

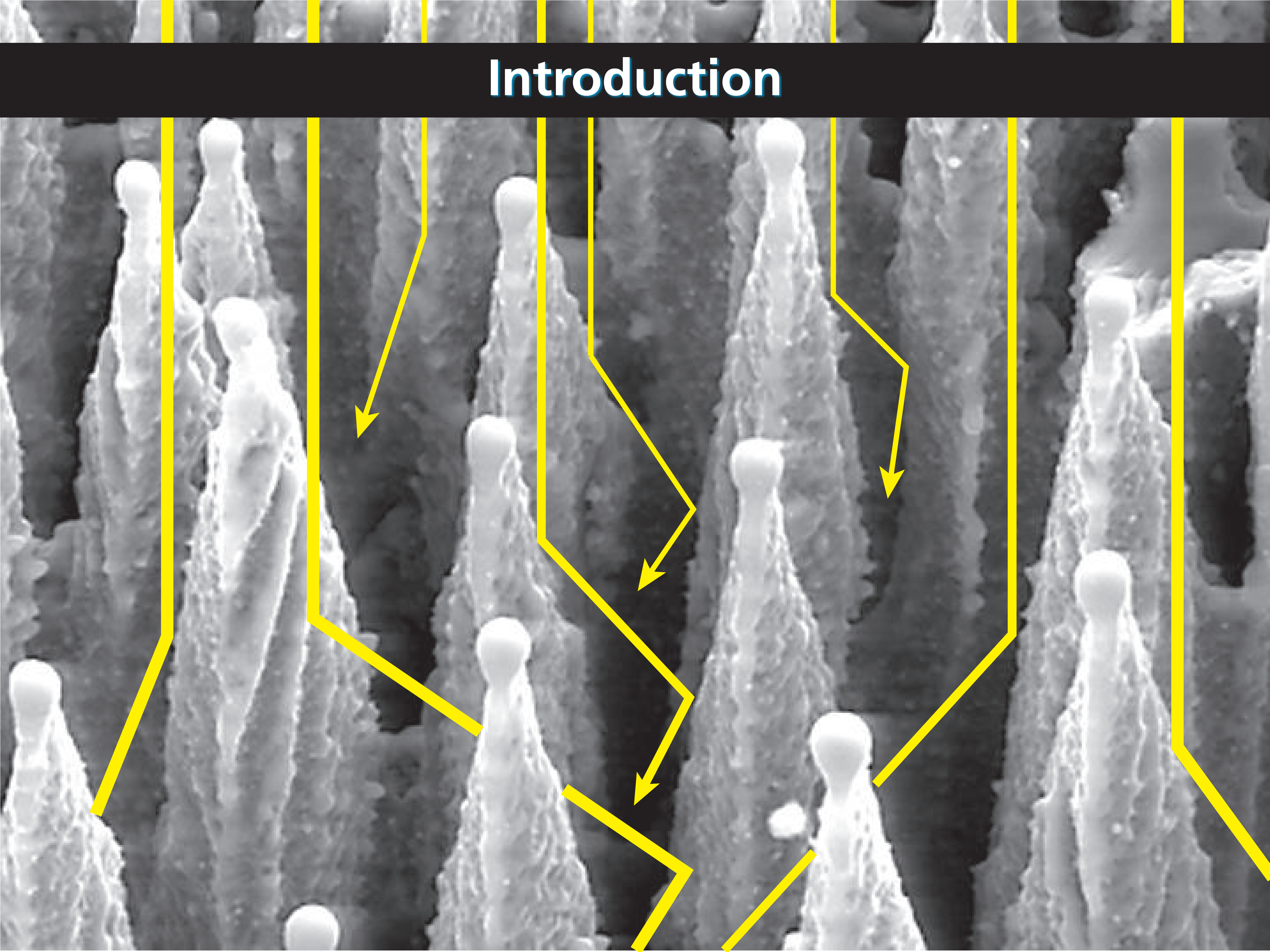

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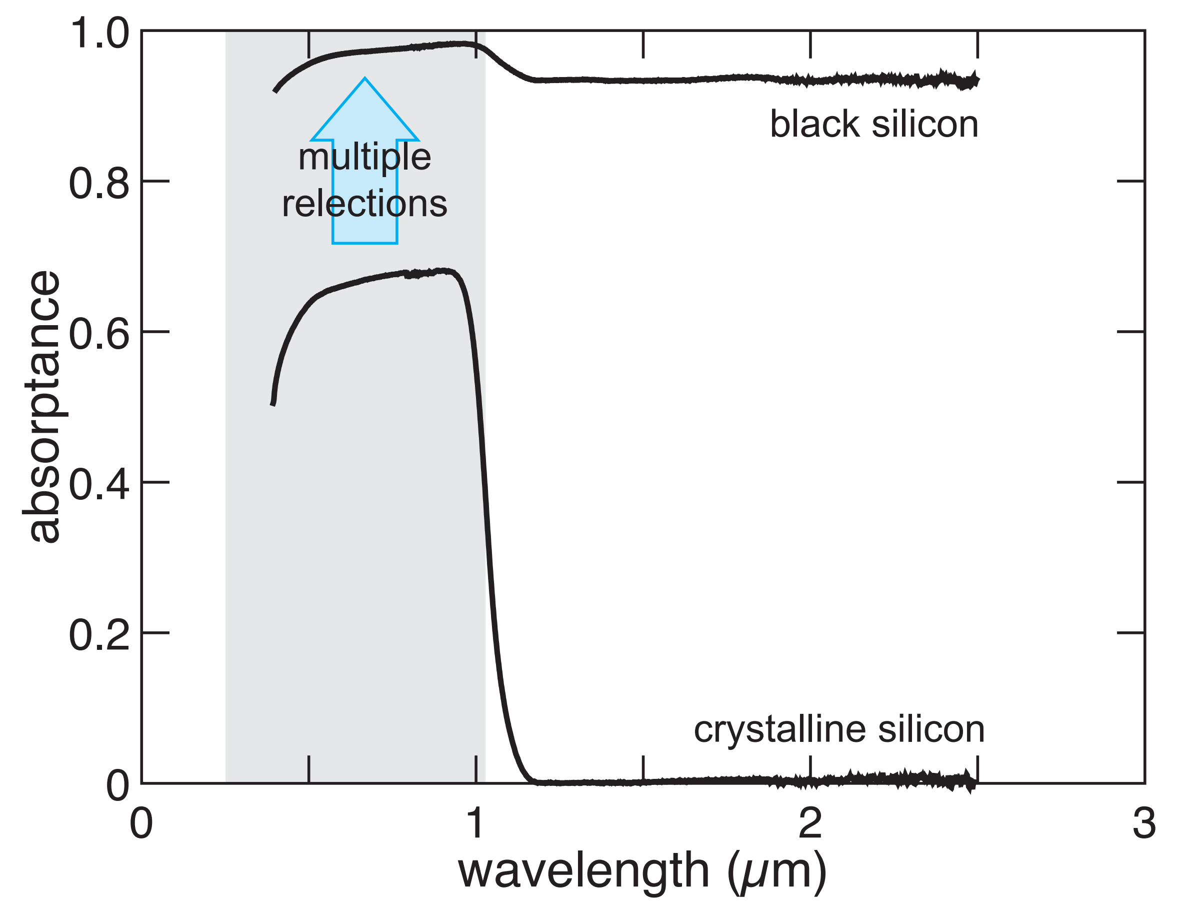


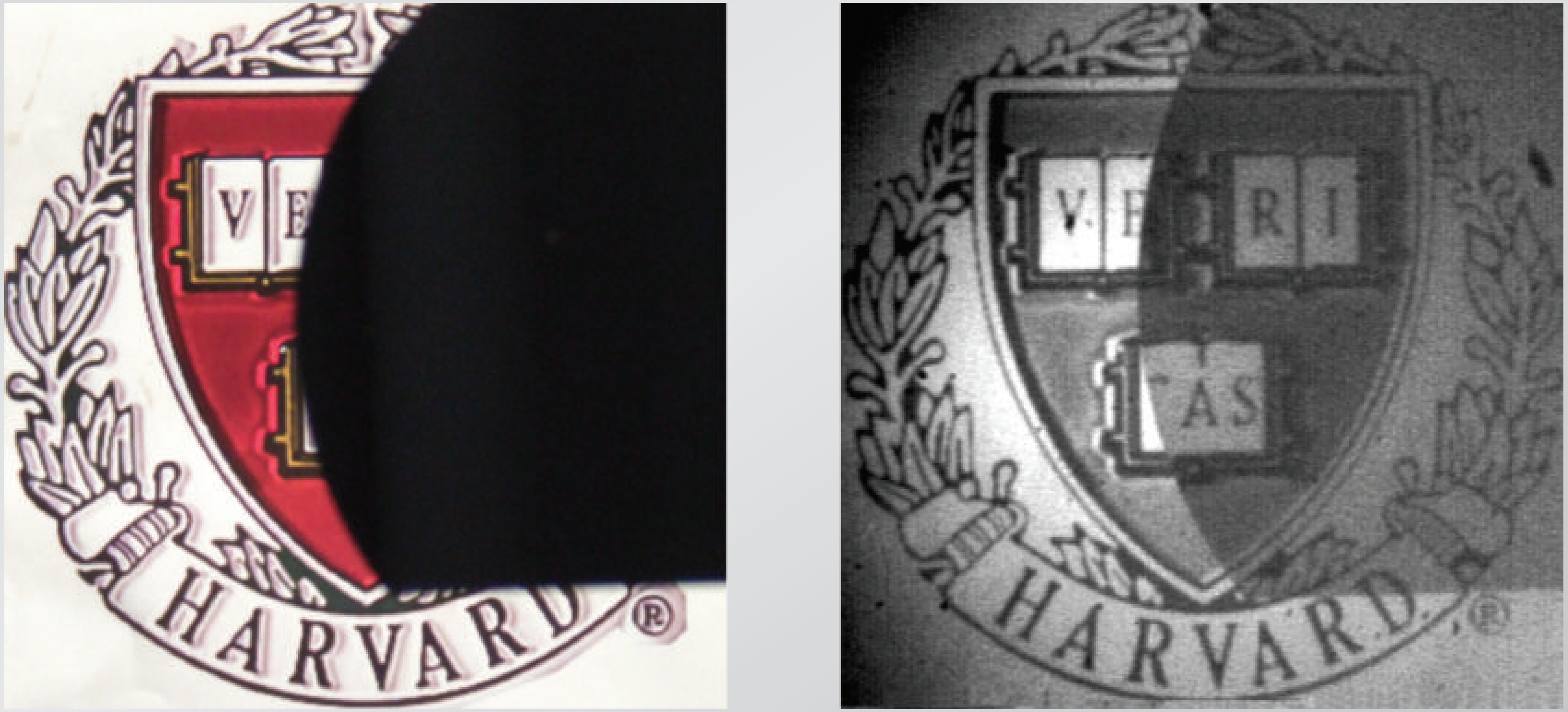
Introduction

silicon transparent in near IR

visible

Introduction

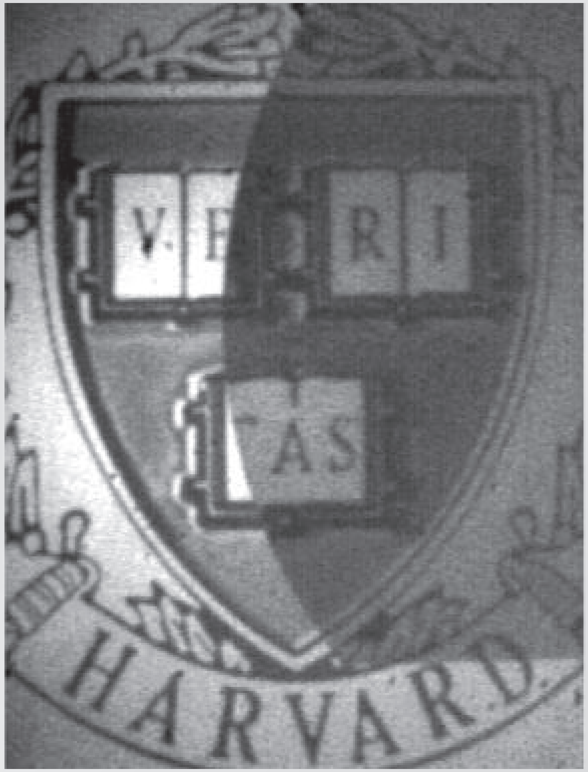
silicon transparent in near IR



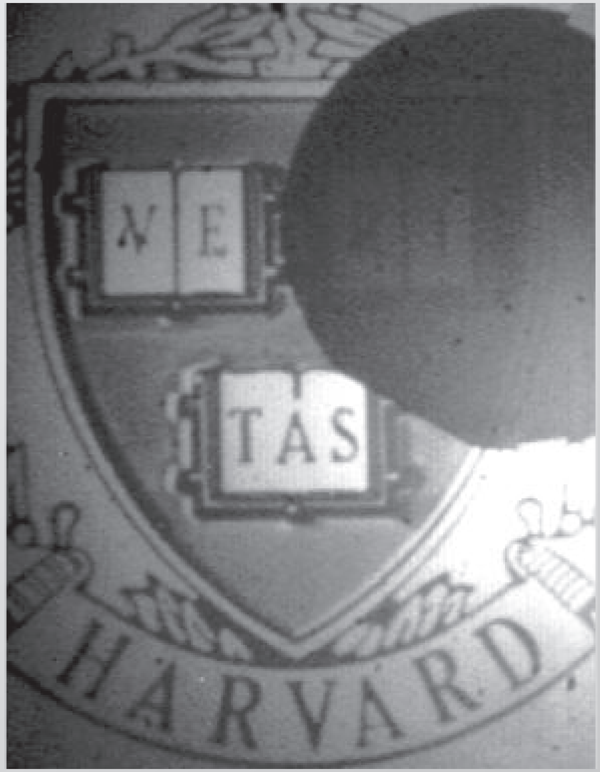
Introduction

roughening doesn't change IR transmission…

polished



unpolished



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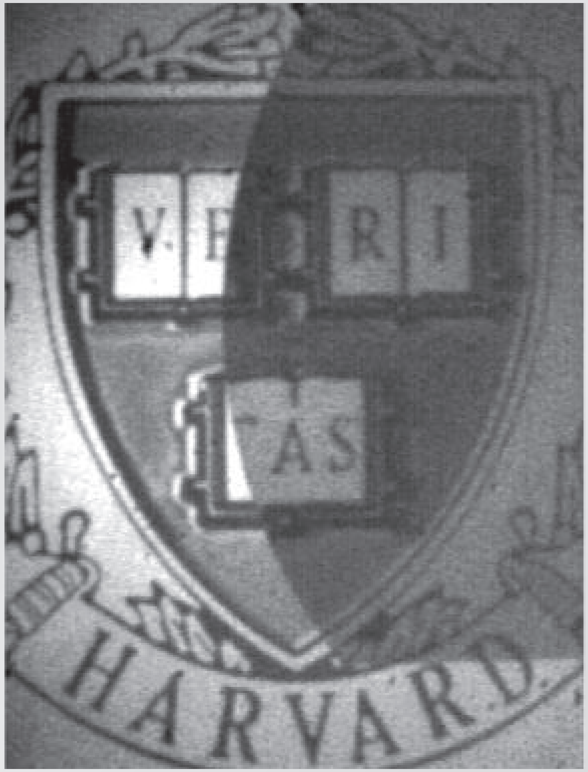

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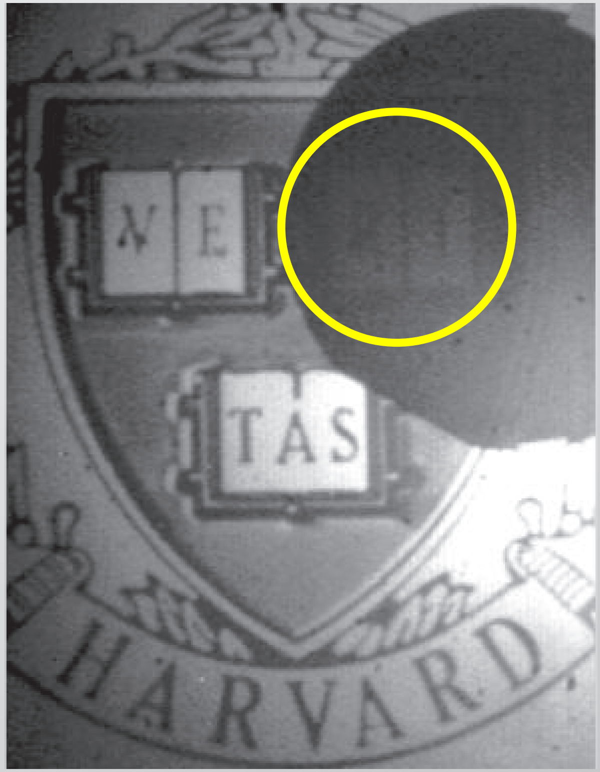
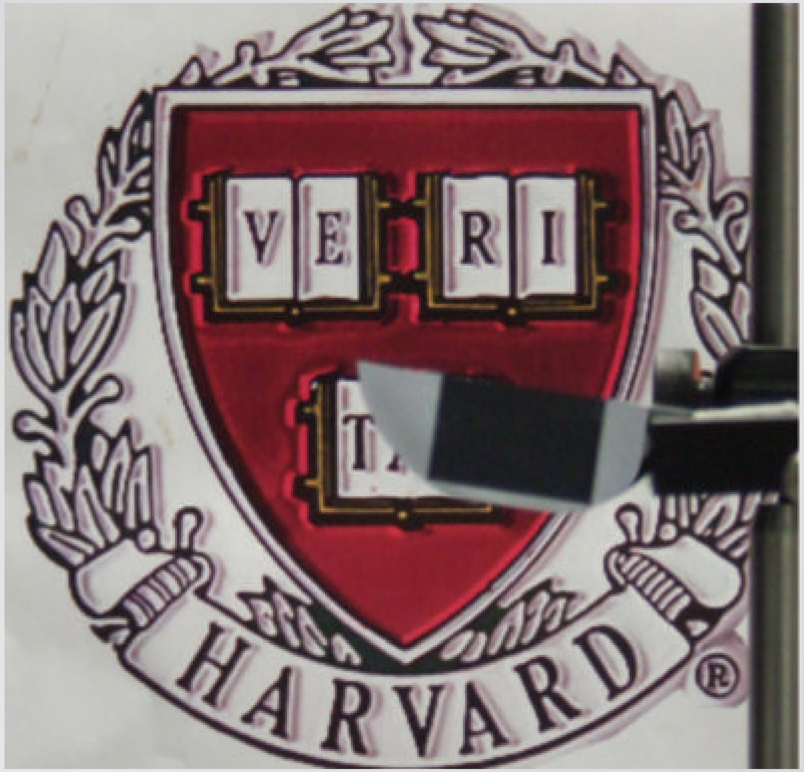


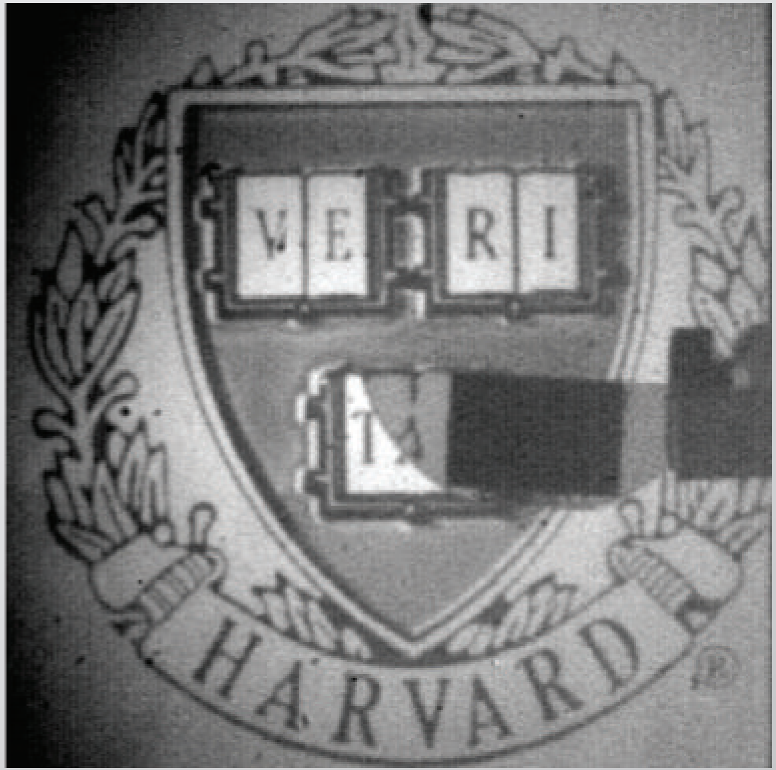
Introduction

…but black silicon blocks IR completely

visible



near IR



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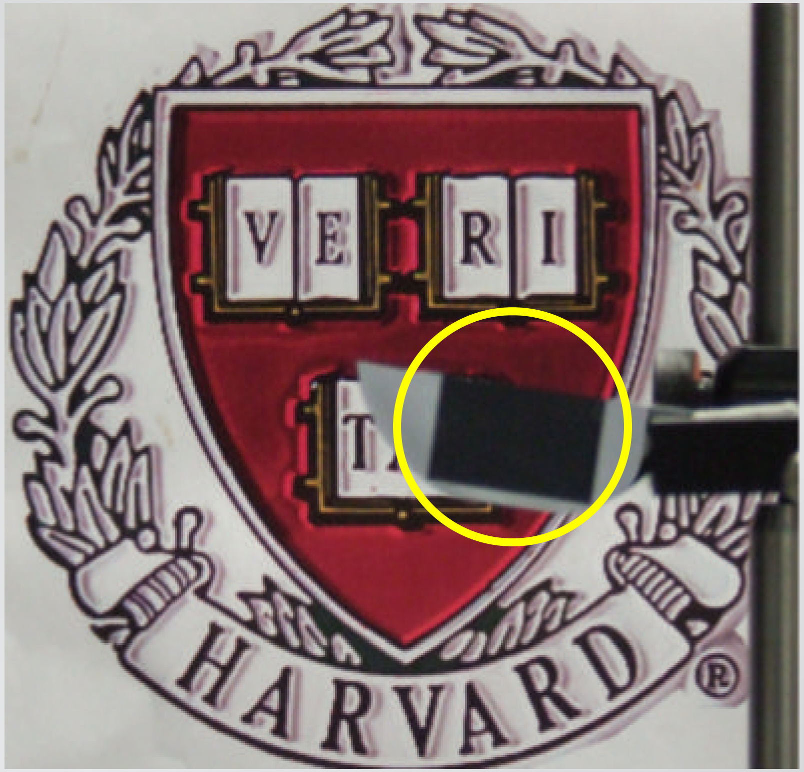

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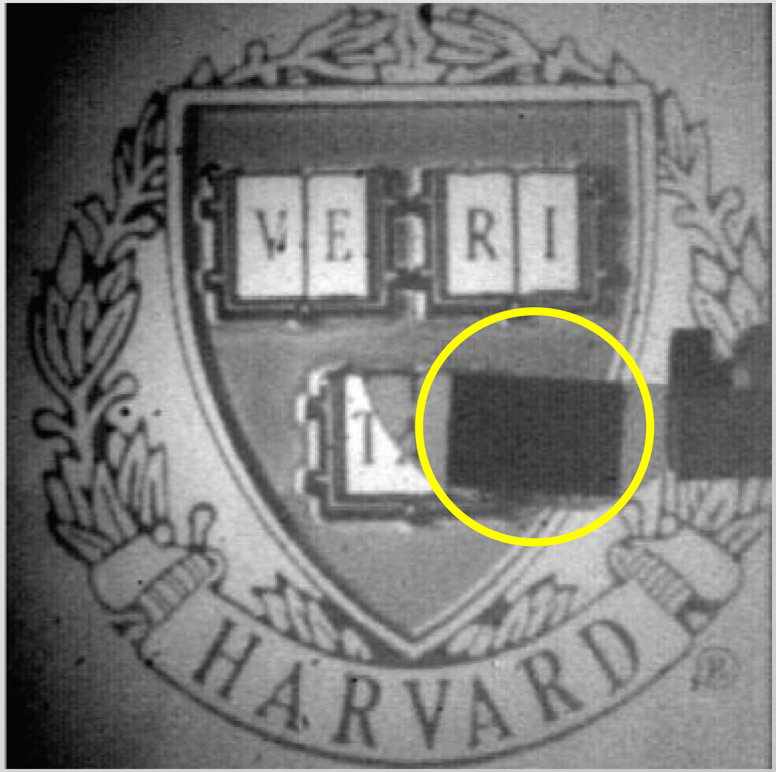
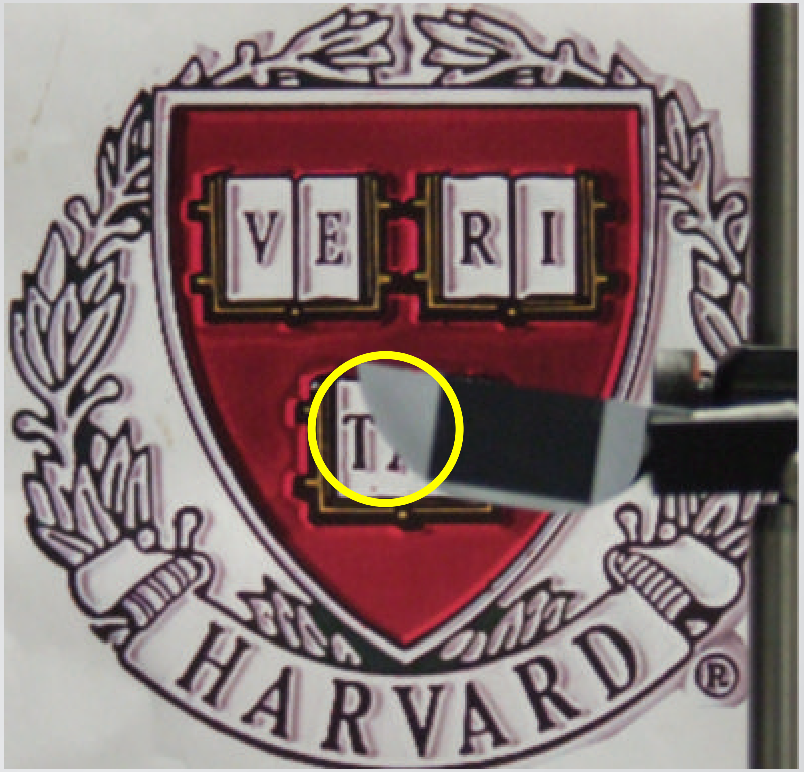


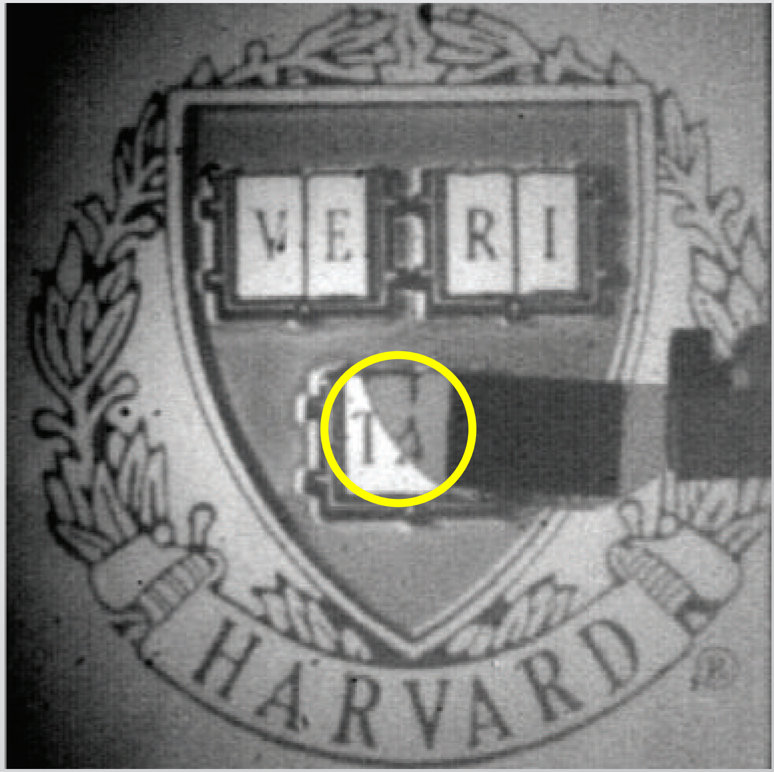
Introduction

black silicon completely black in IR

visible



near IR



Introduction

band structure changes: defects and/or impurities

Introduction

a decade of research

OPTICAL

UV-VIS-NIR
FTIR
photoluminescence
PTD spectroscopy
UPS
XPS

ELECTRONIC

Hall measurements
conductivity
IV rectification
c-AFM

responsivity
photoconductivity

STRUCTURAL

SEM
TEM
EDX
SAD
EXAFS
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ion channeling

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a decade of research

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carrier concentration
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junction properties

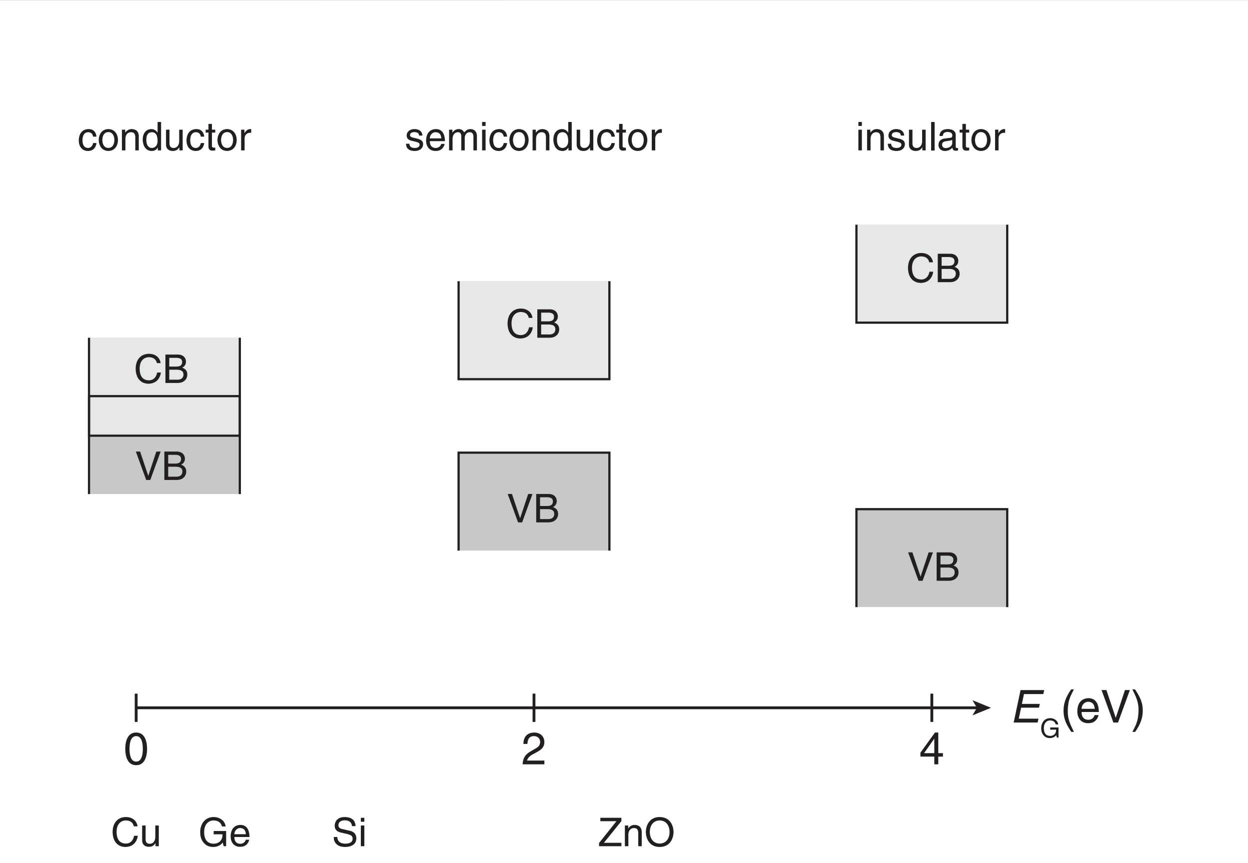
Introduction

a decade of research

OPTICAL	ELECTRONIC	STRUCTURAL
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	morphology composition atomic structure

Introduction

new process & new class of material!



Introduction

substrate/dopant combinations

dopants:

N	O	F
P	S	Cl
	Se	
Sb	Te	

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Si Ge ZnO InP GaAs

Ti Ag Al Cu Pd Rh Ta Pt

Introduction

focus on chalcogen-doped silicon

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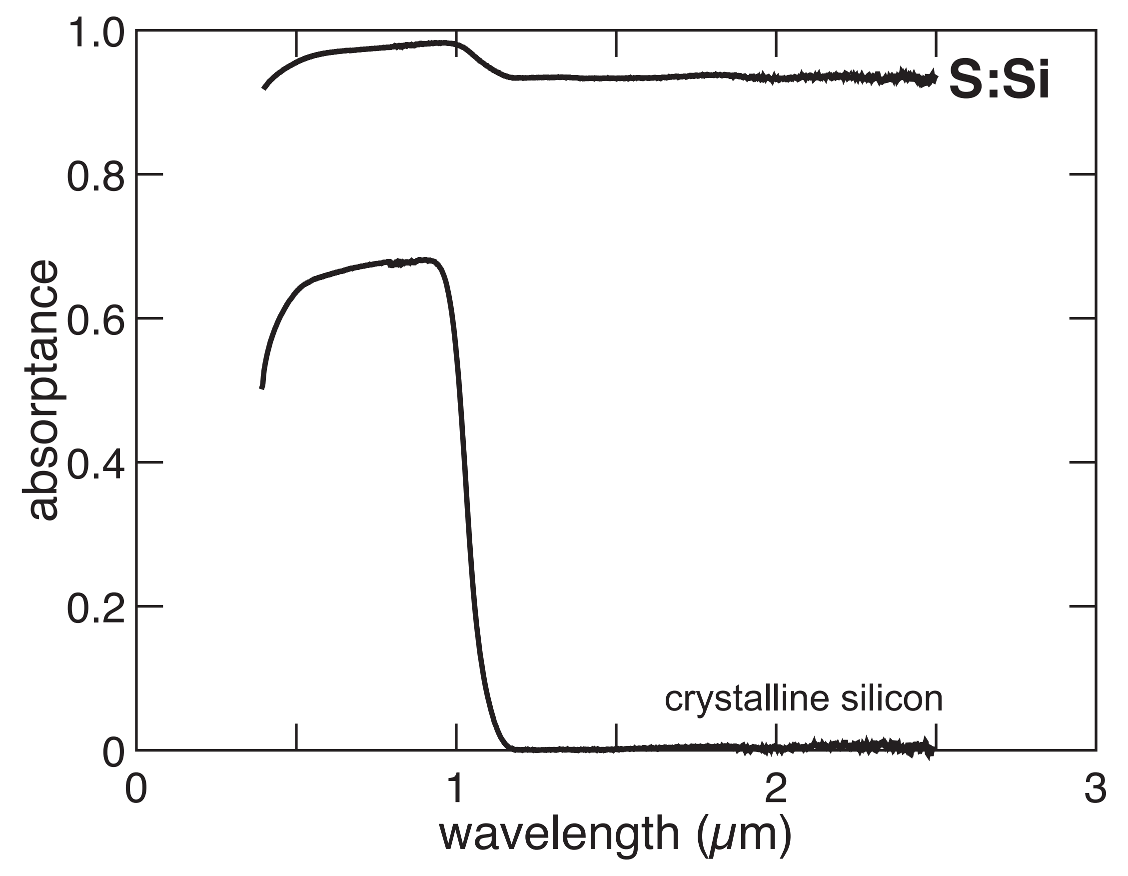

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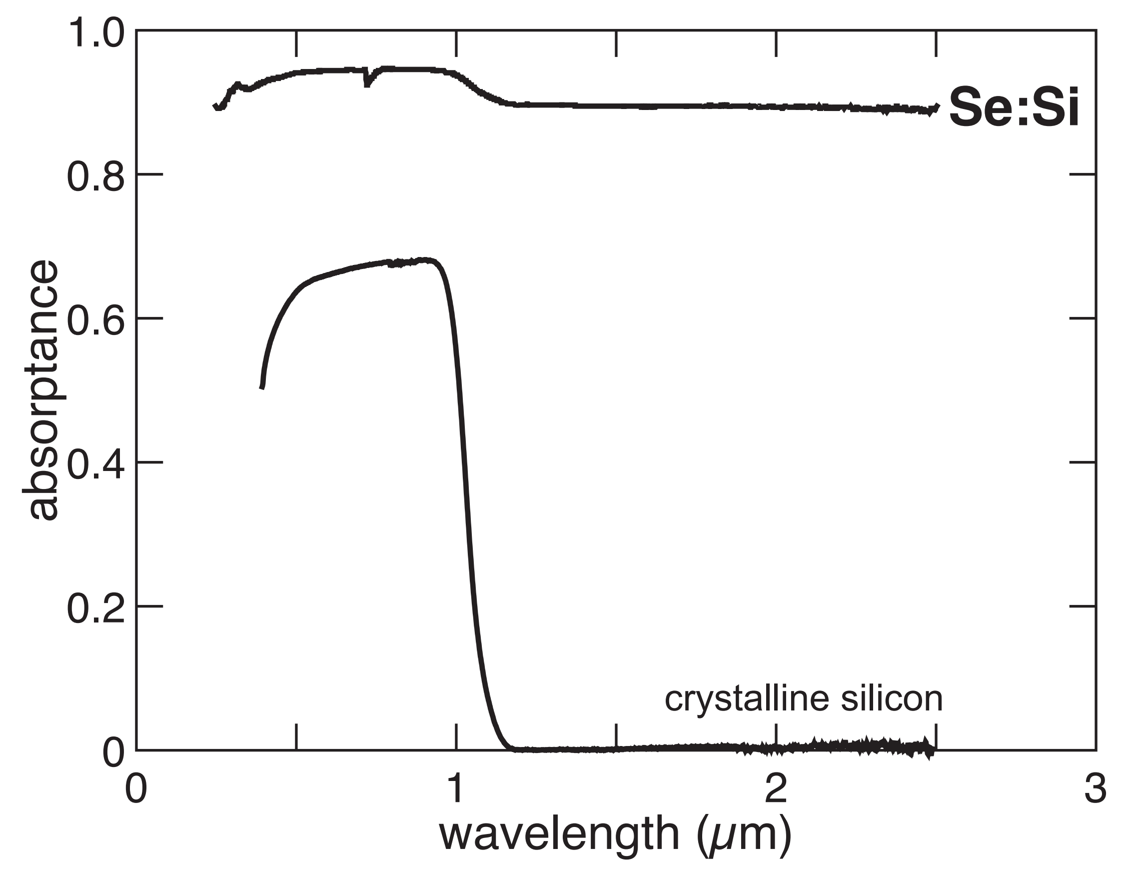
focus on chalcogen-doped silicon



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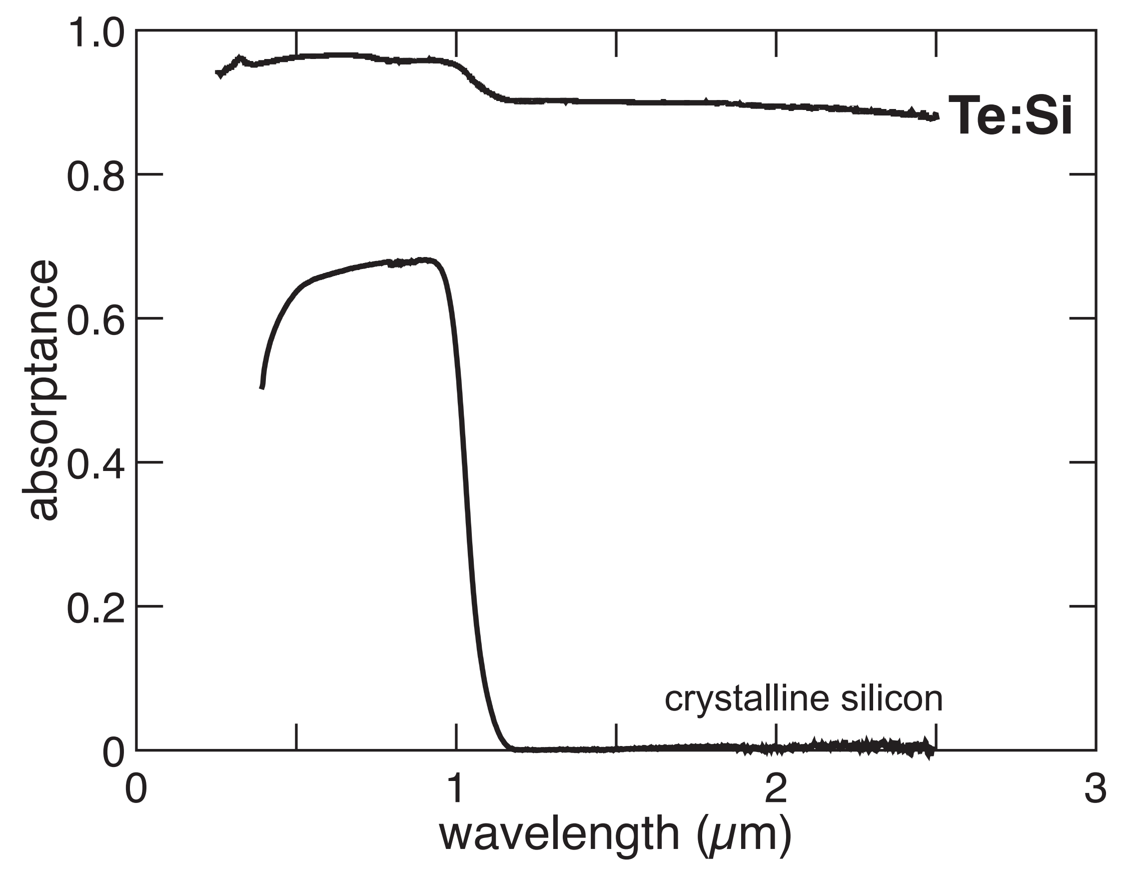
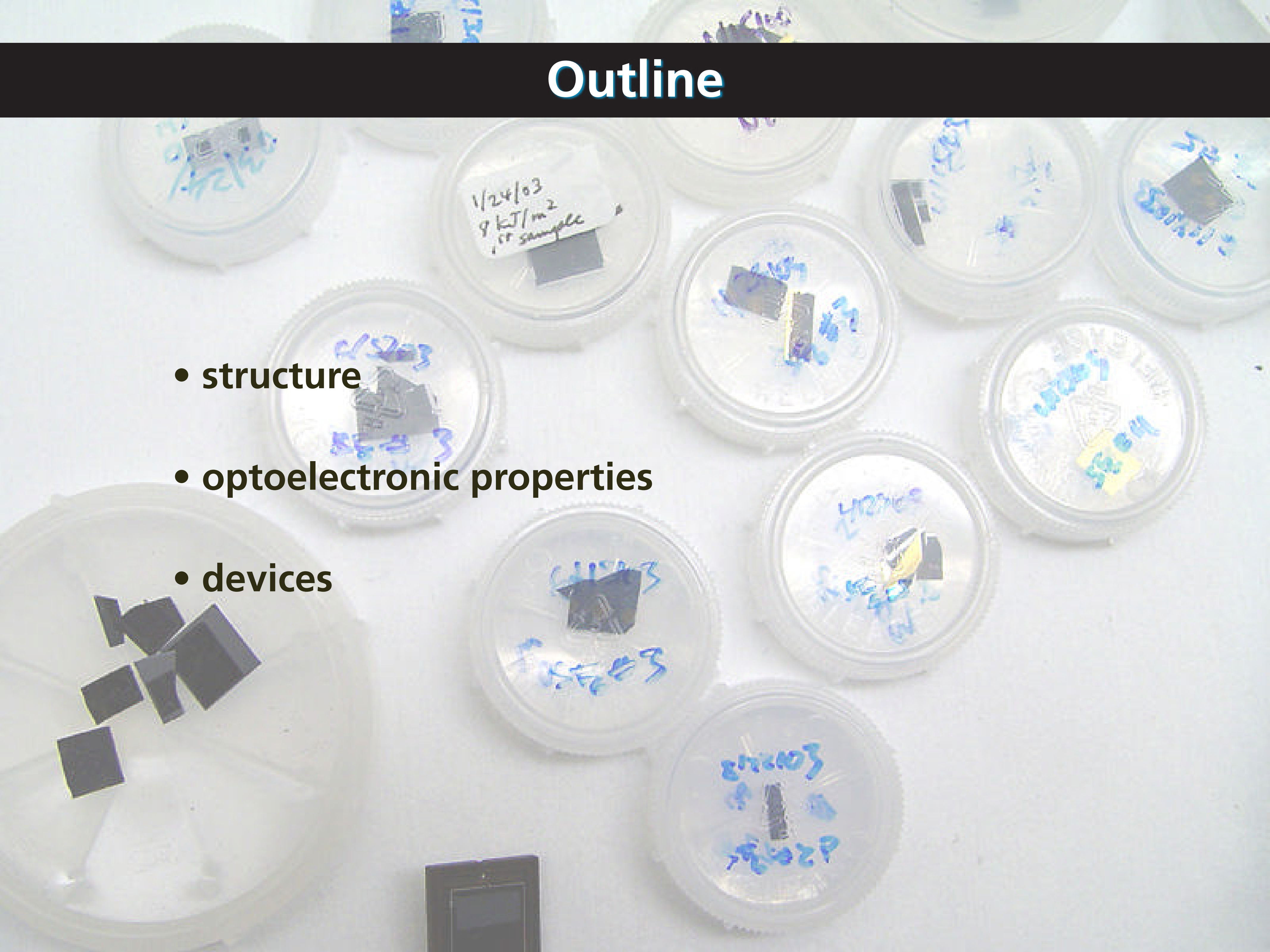
focus on chalcogen-doped silicon

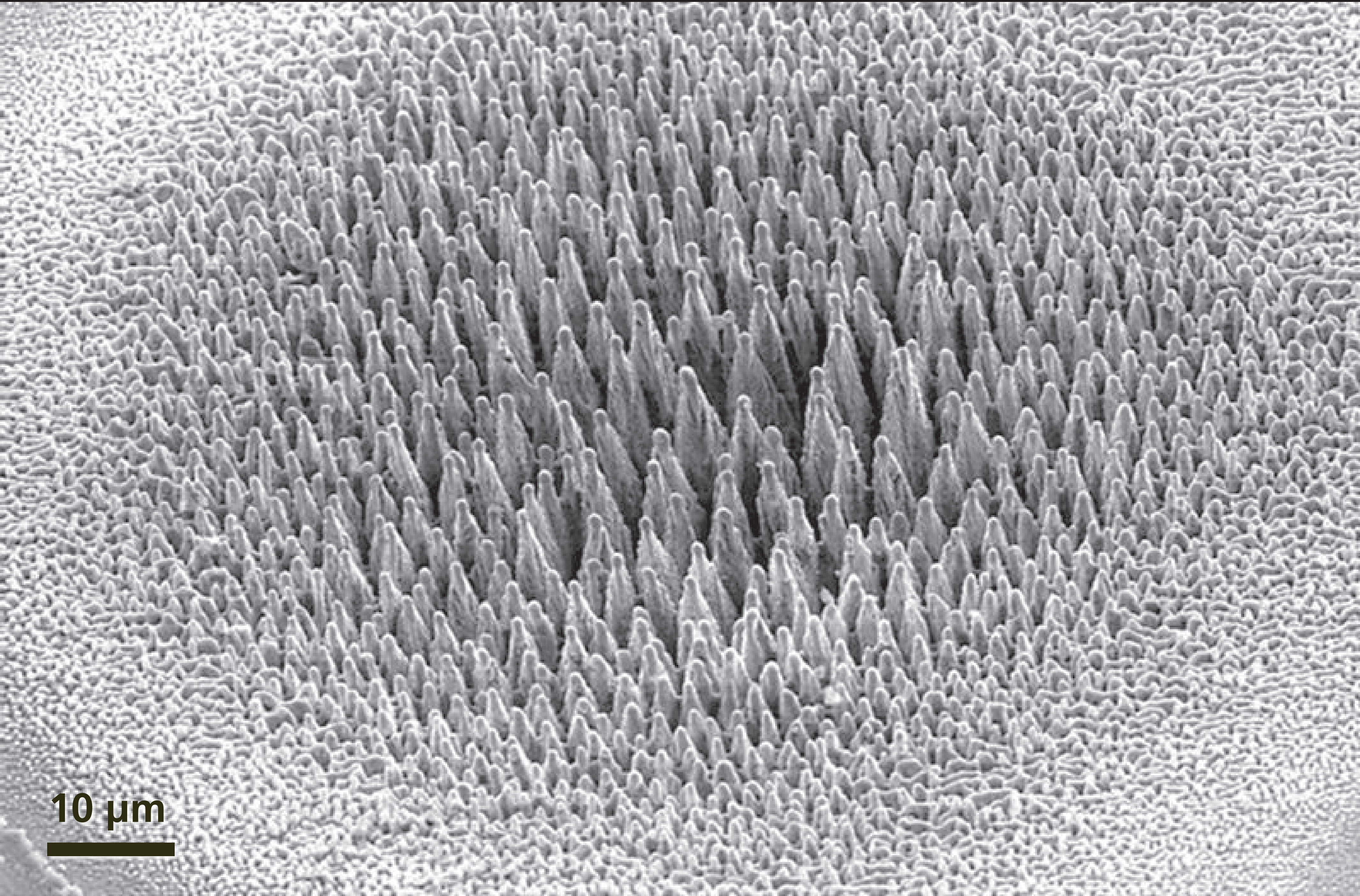


Outline

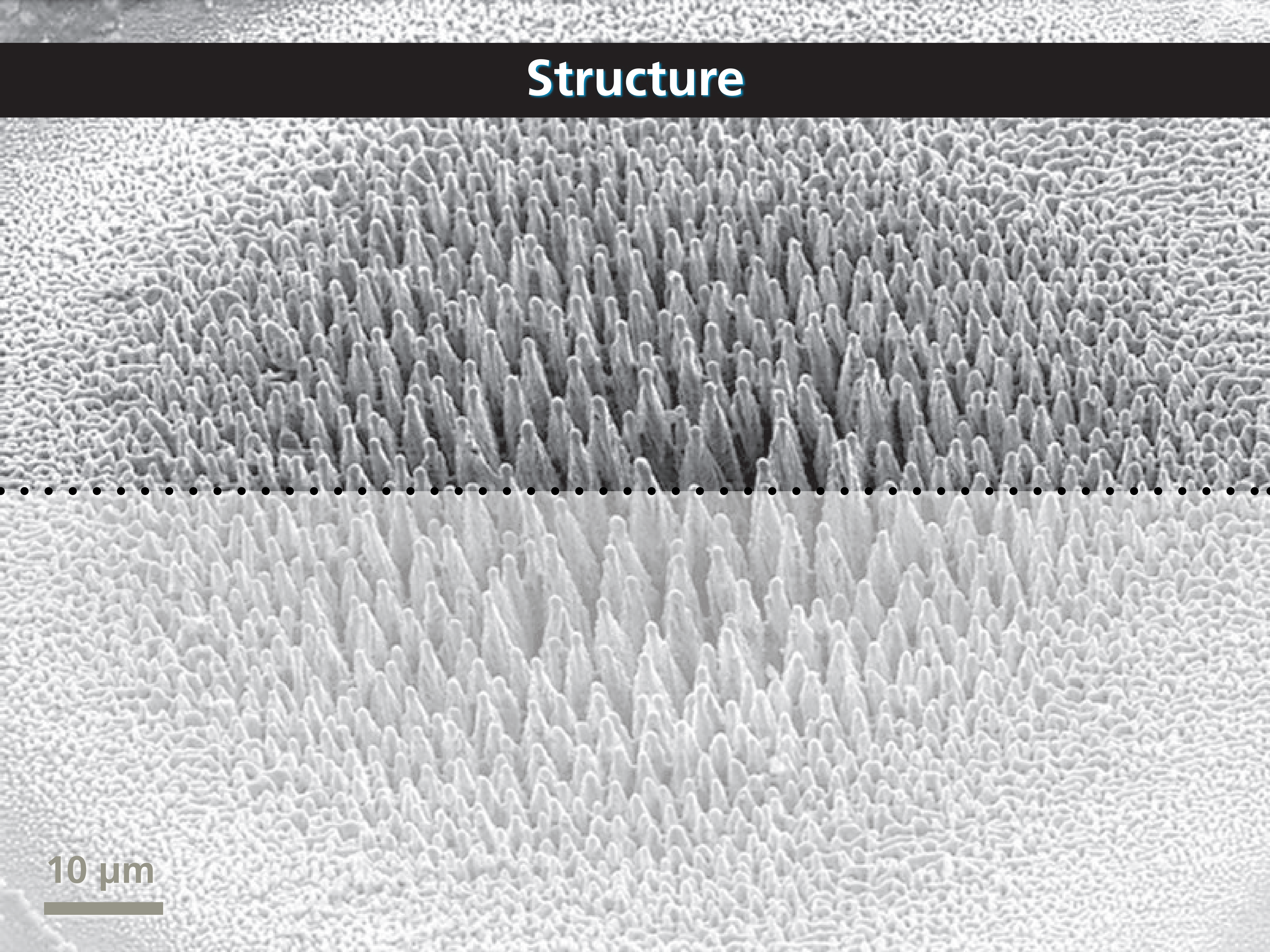


- structure
- optoelectronic properties
- devices

Structure



Structure



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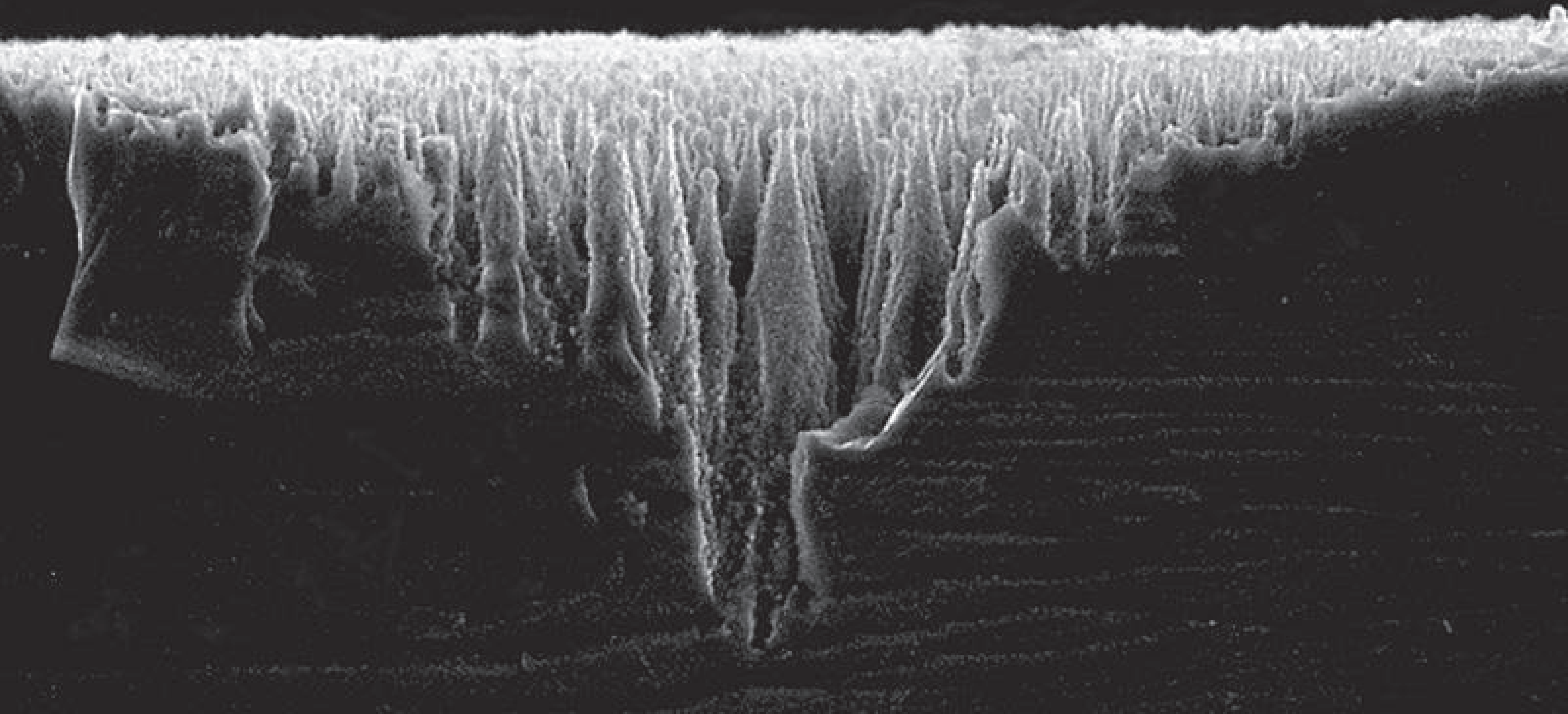

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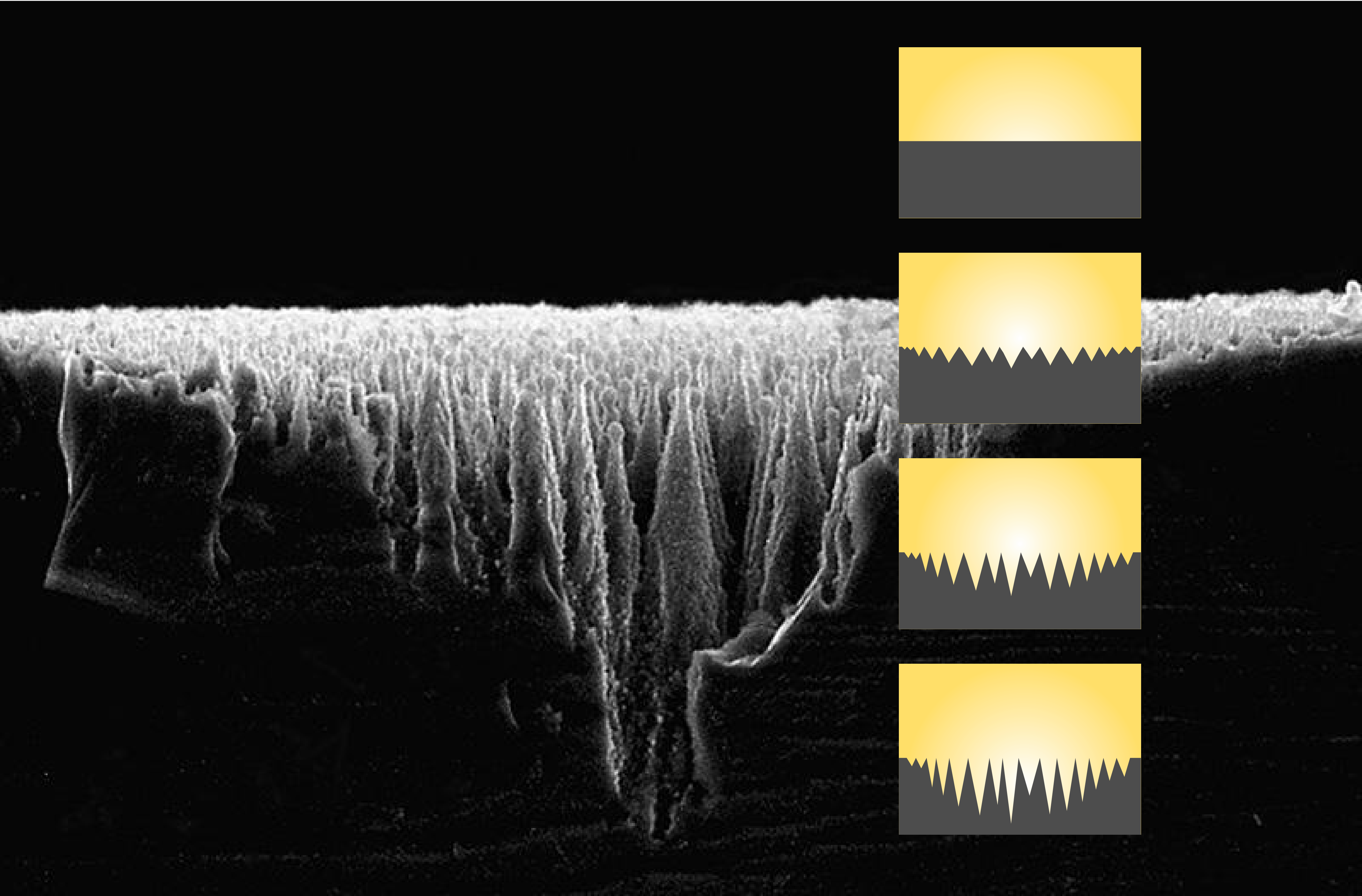

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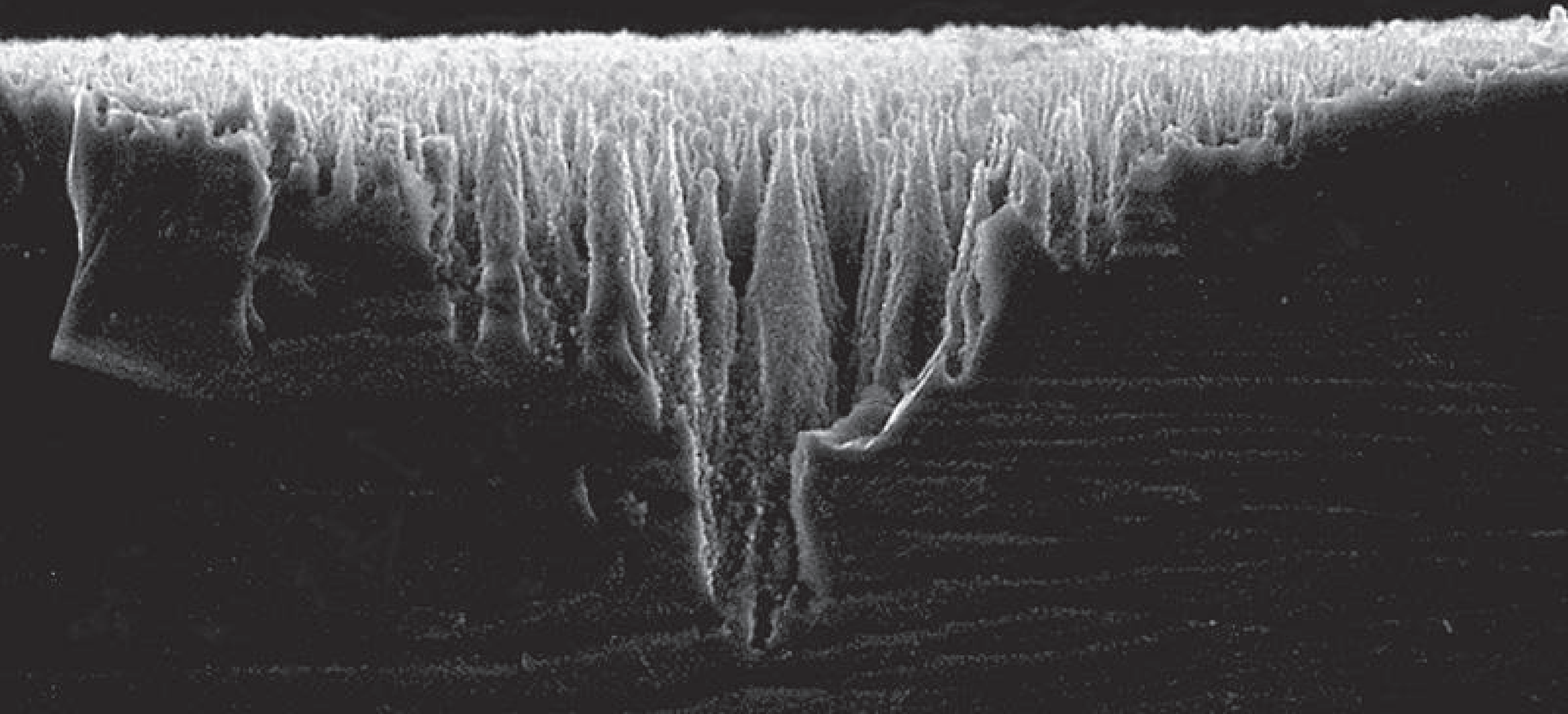

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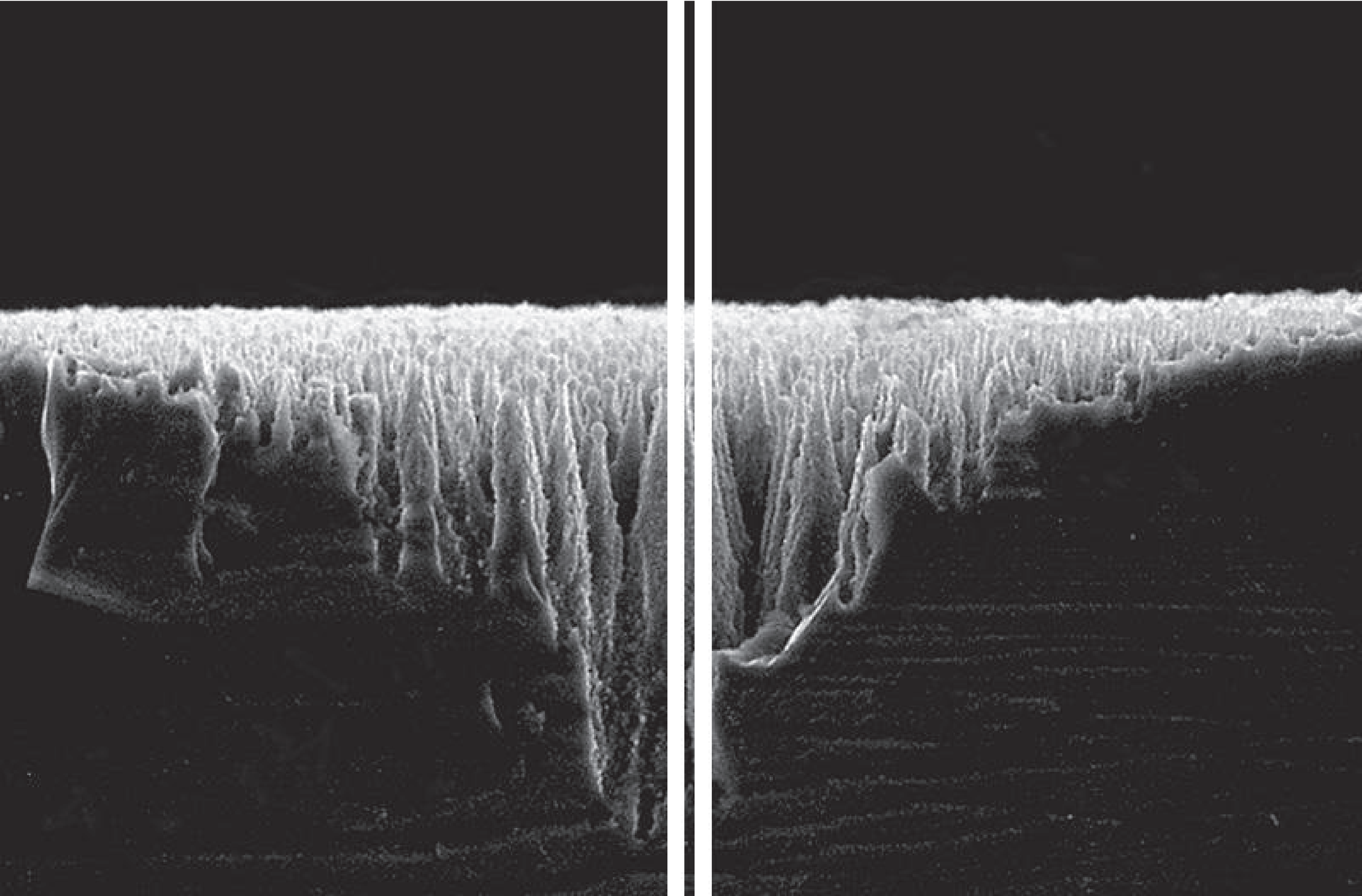

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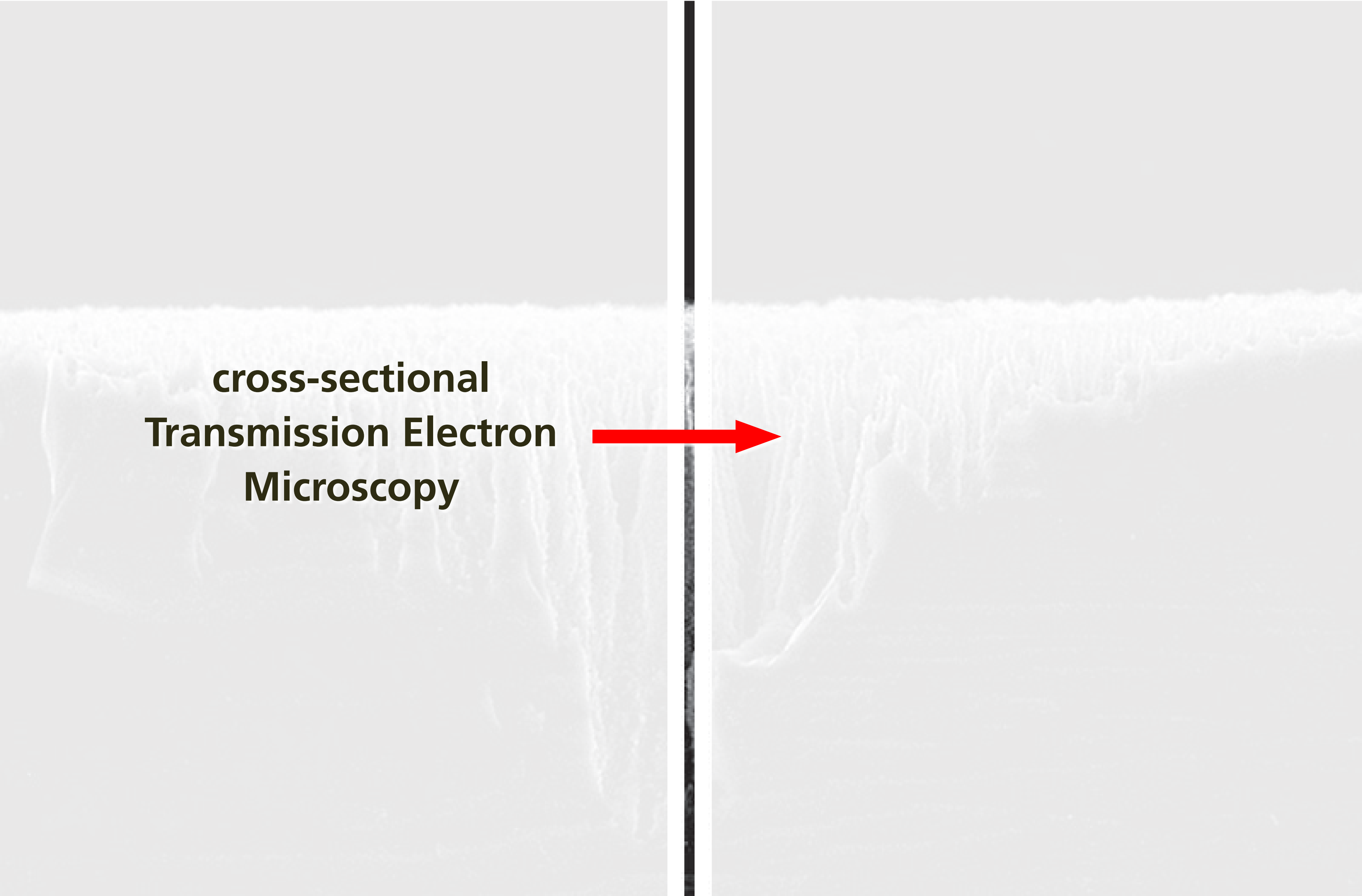
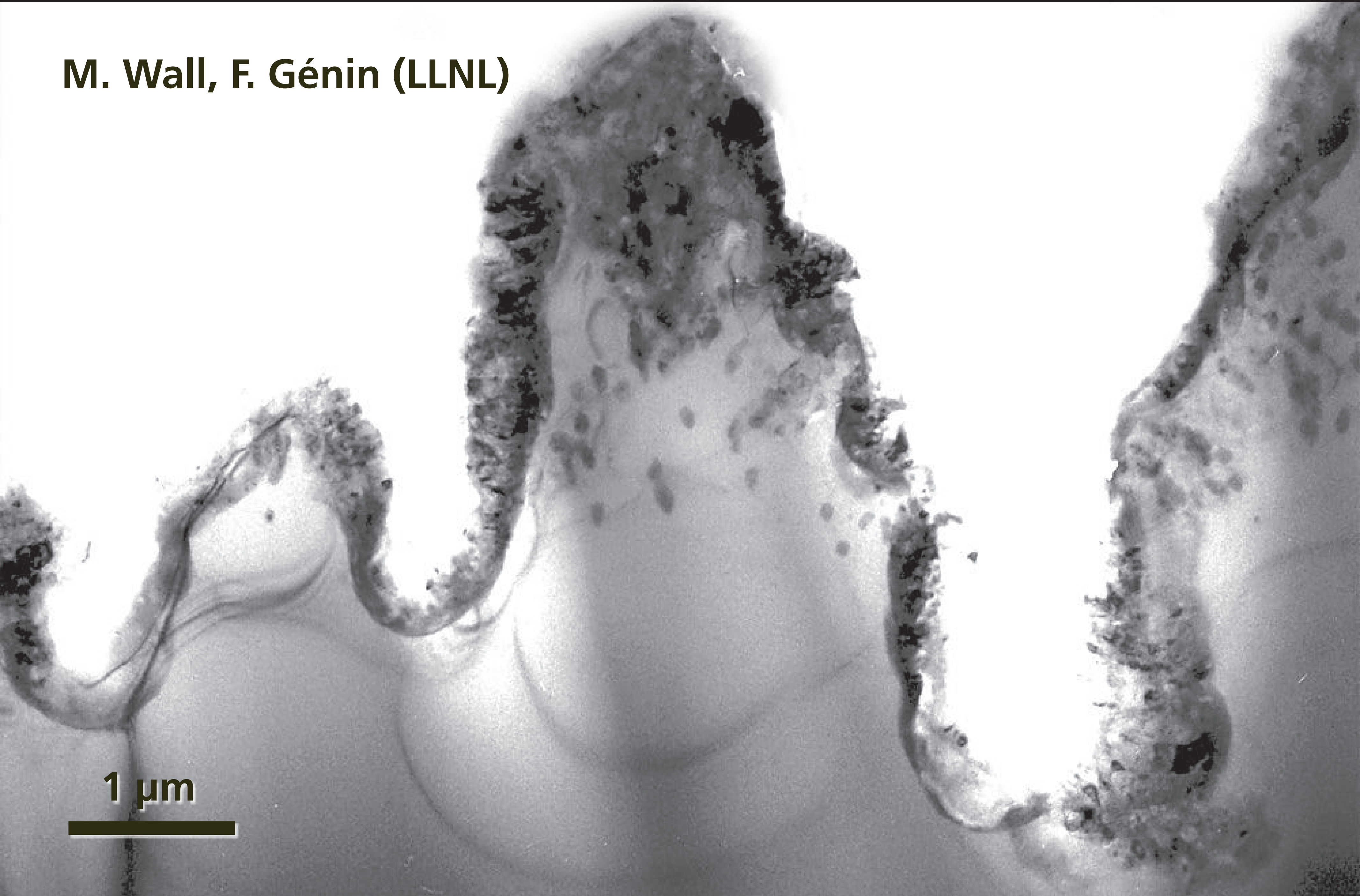


cross-sectional Transmission Electron Microscopy

Structure

M. Wall, F. Génin (LLNL)



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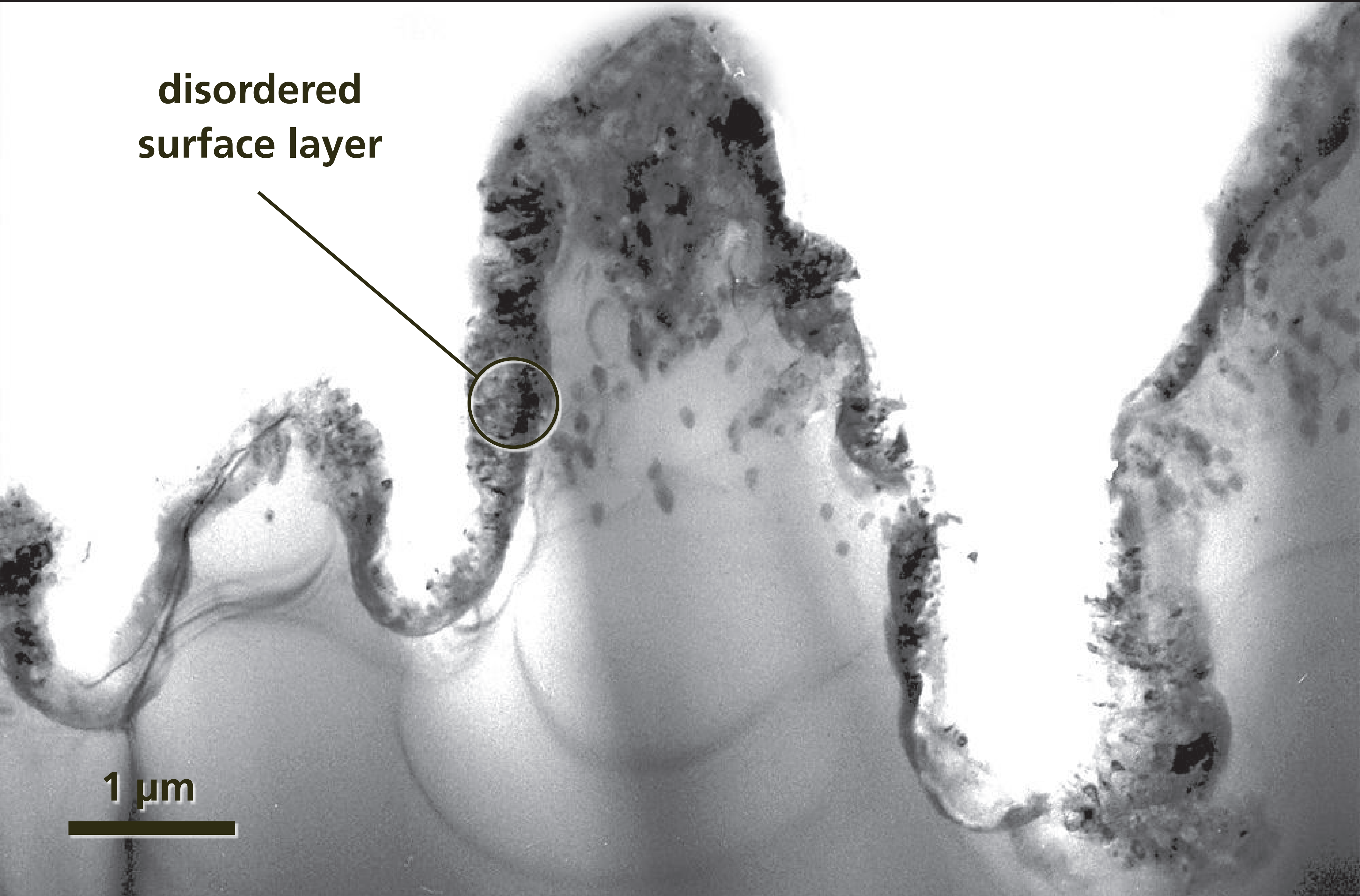

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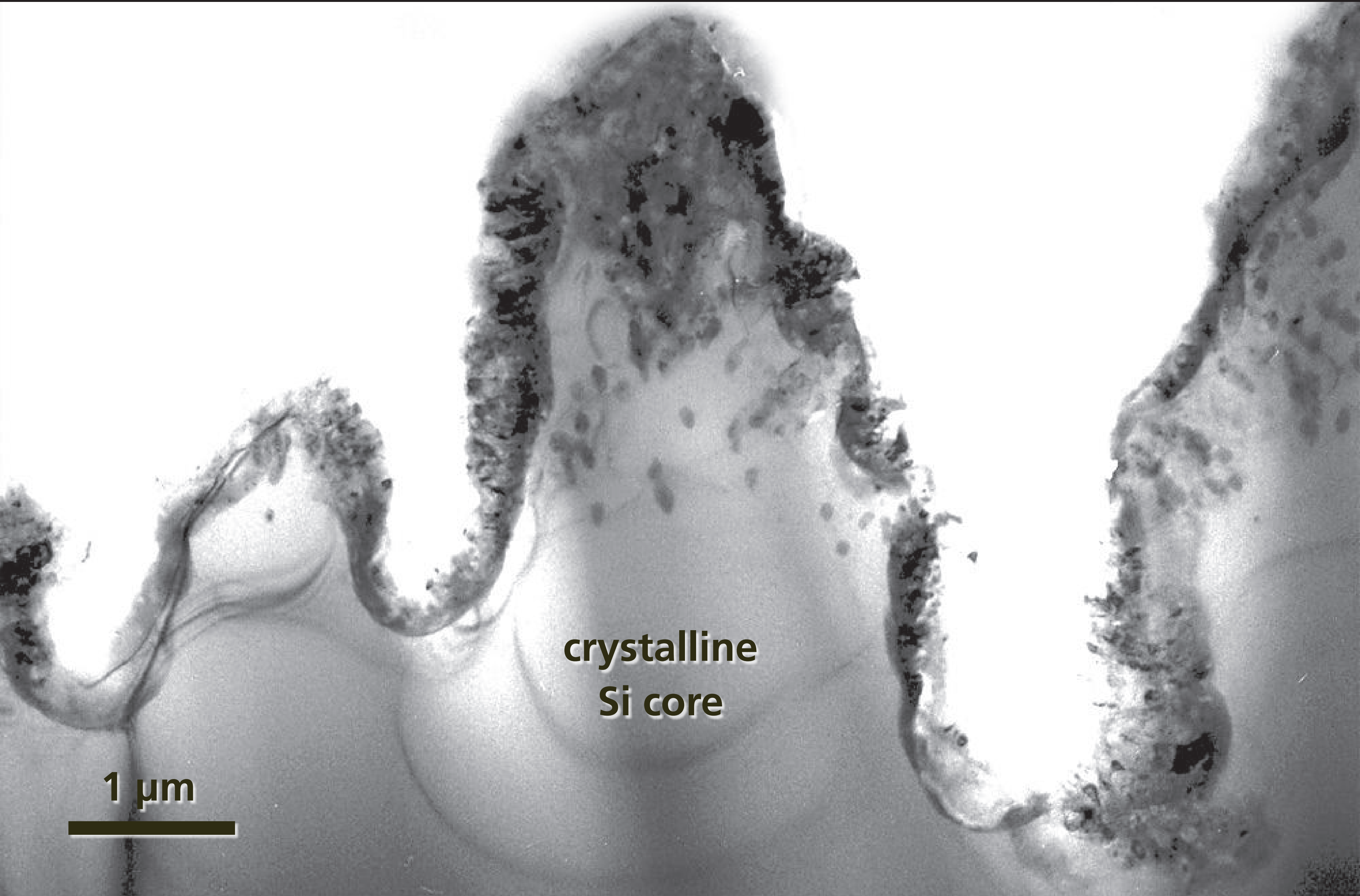

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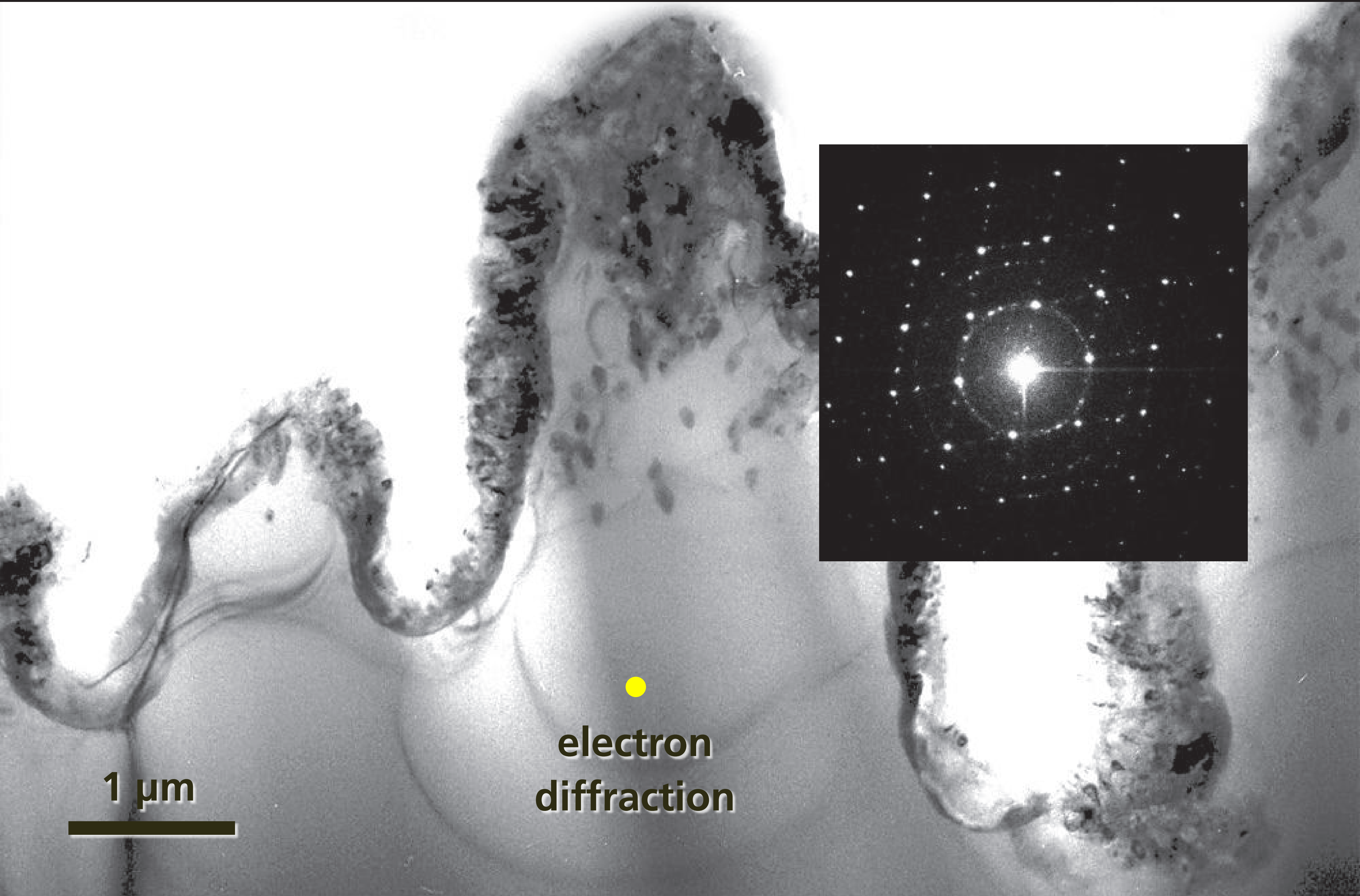

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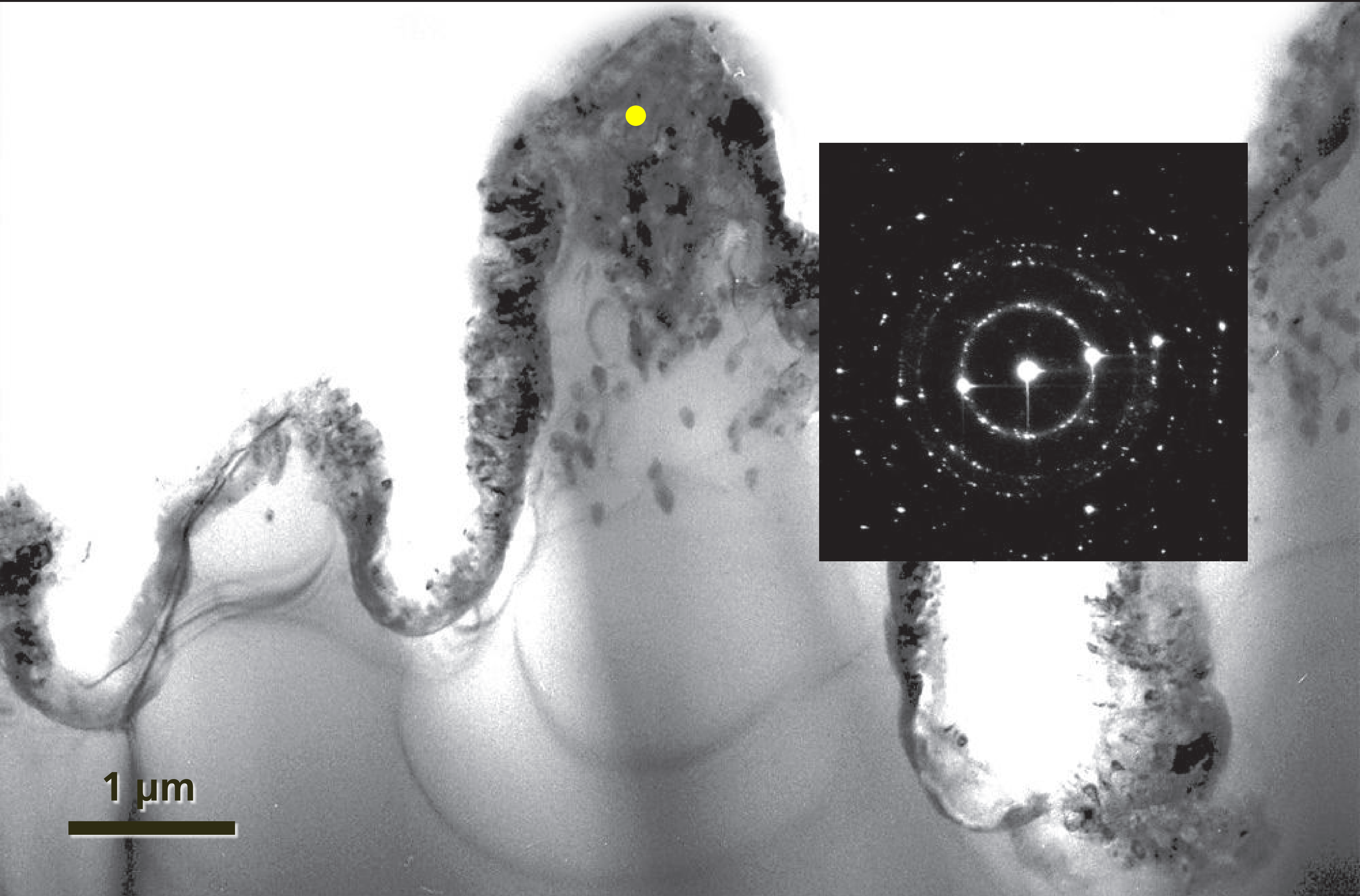

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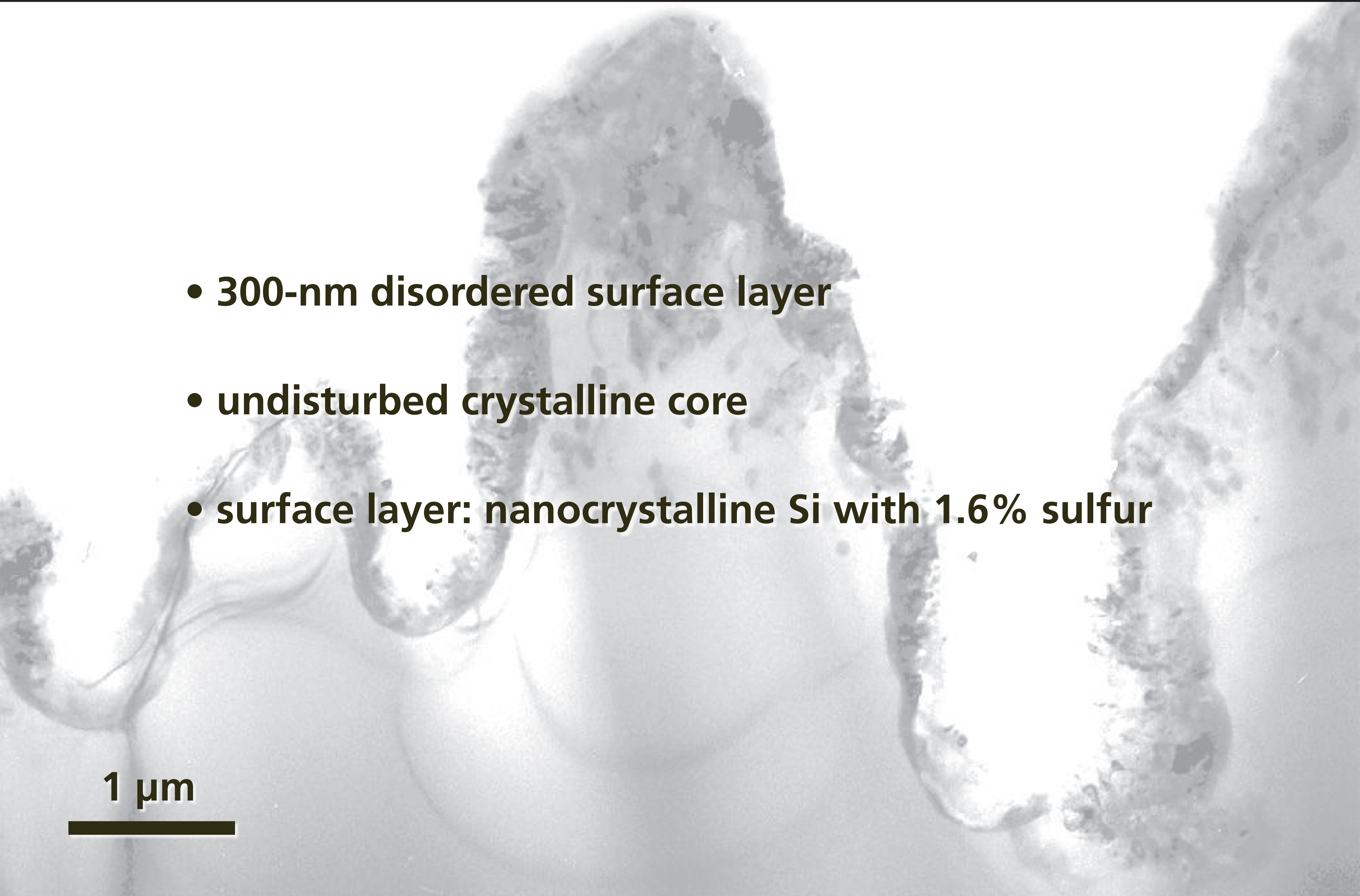


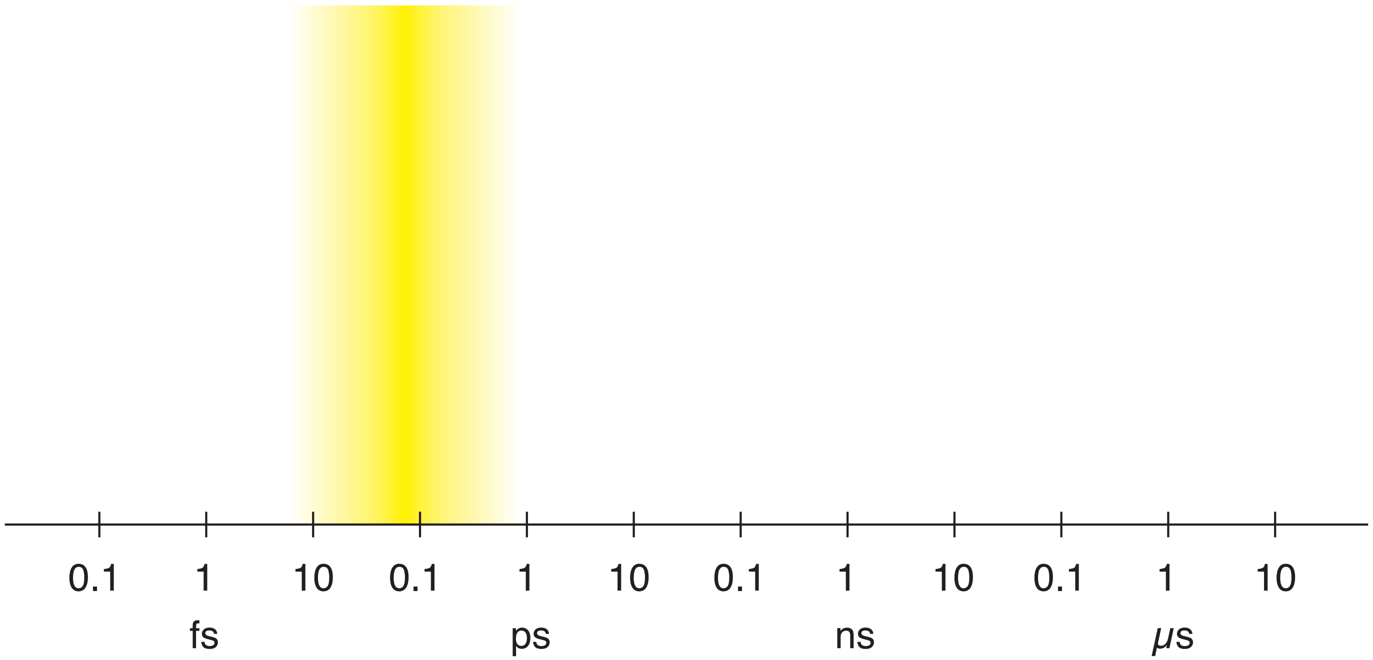
- 300-nm disordered surface layer
- undisturbed crystalline core
- surface layer: nanocrystalline Si with 1.6% sulfur

Structure

two processes: melting and ablation

Structure

relevant time scales



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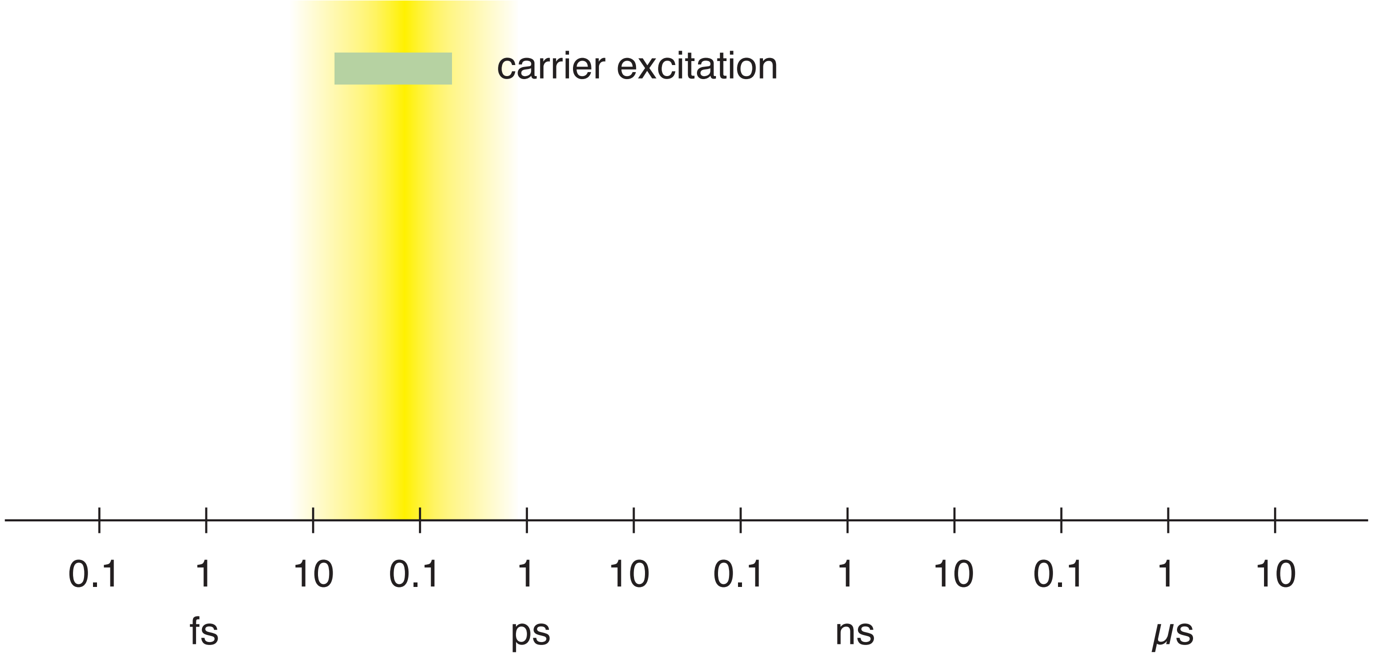

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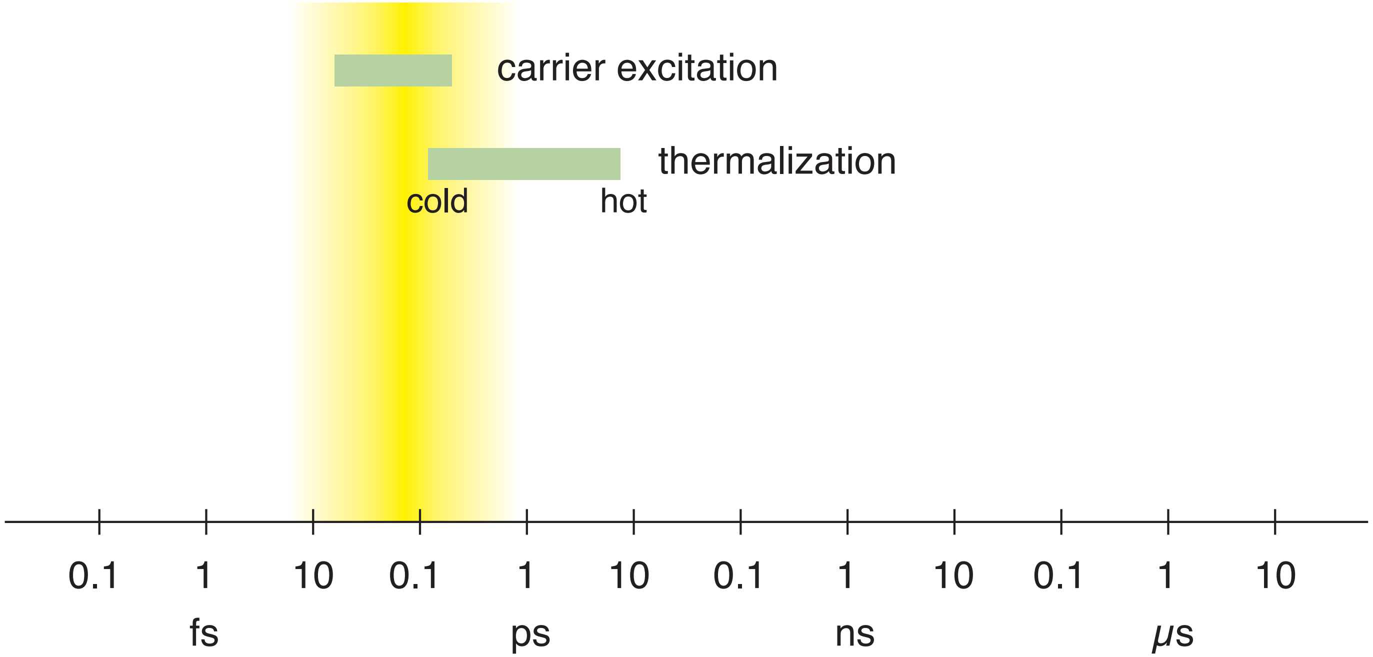

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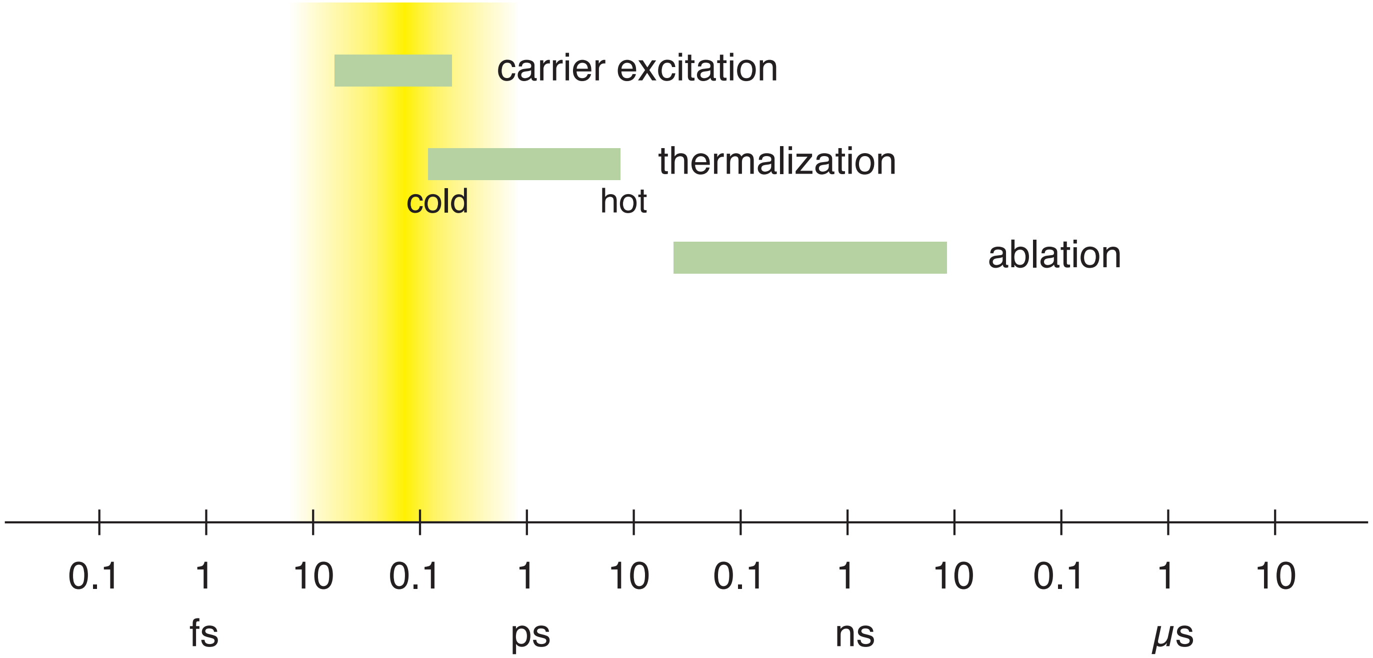

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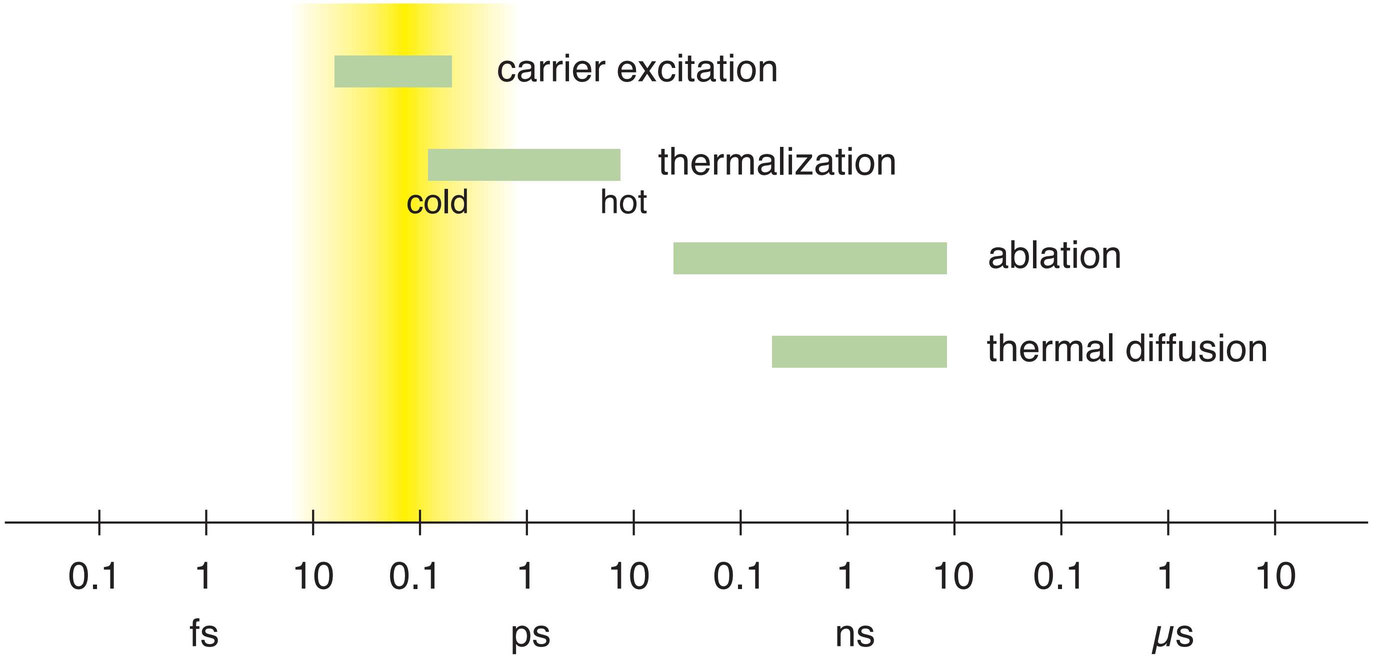

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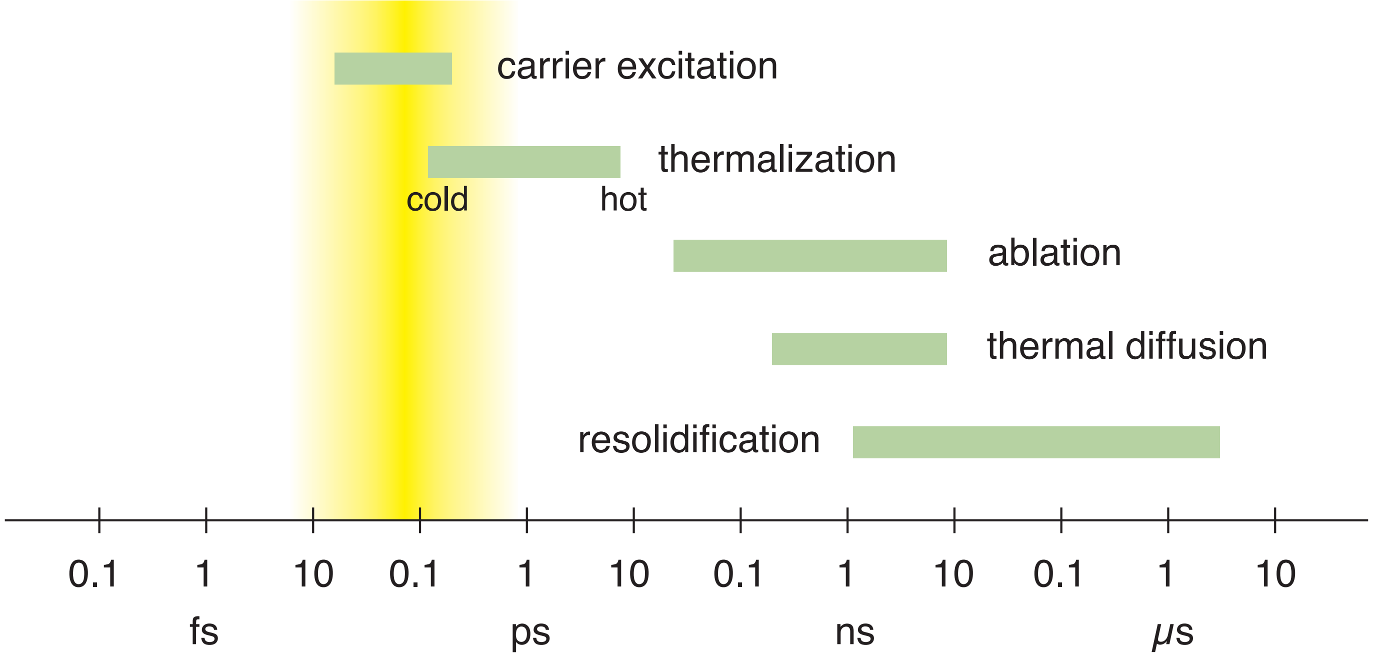

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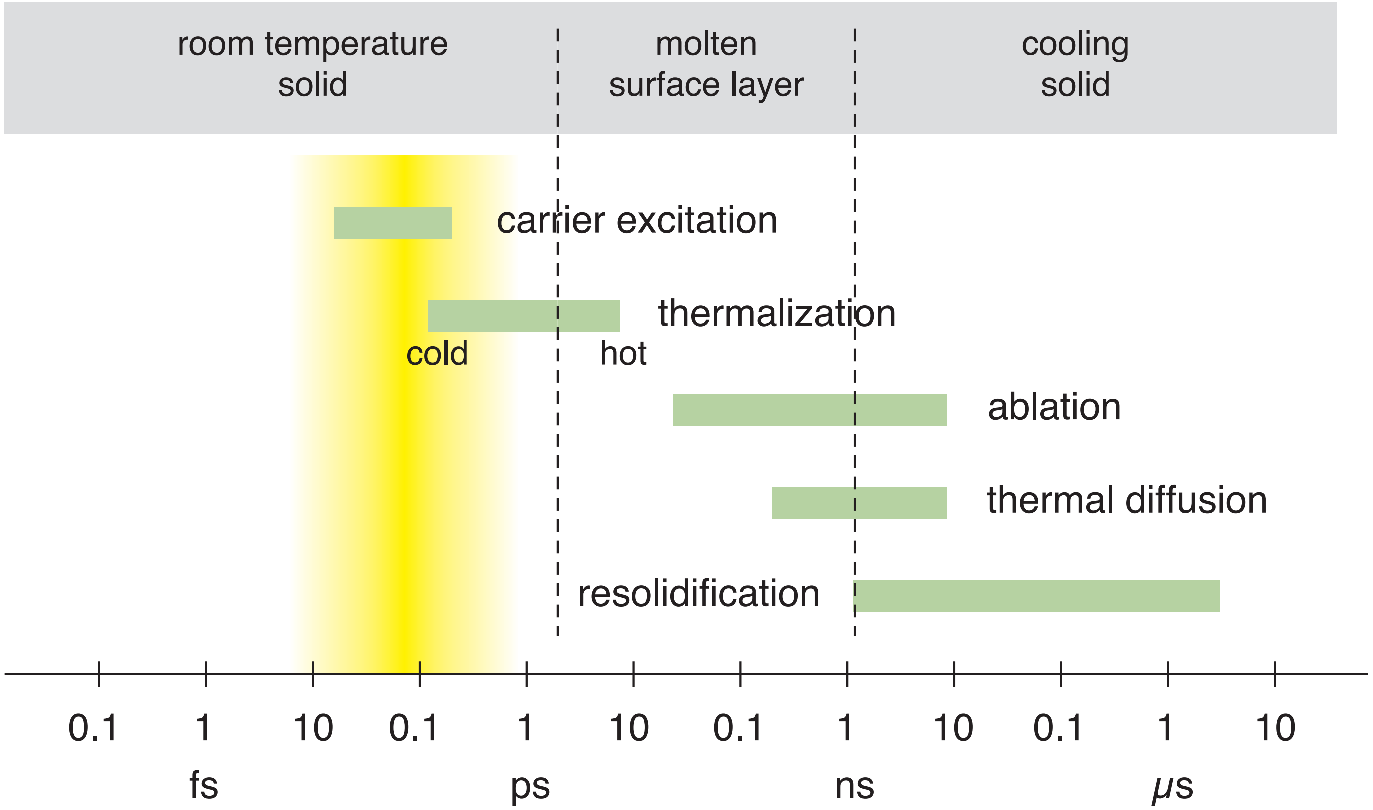

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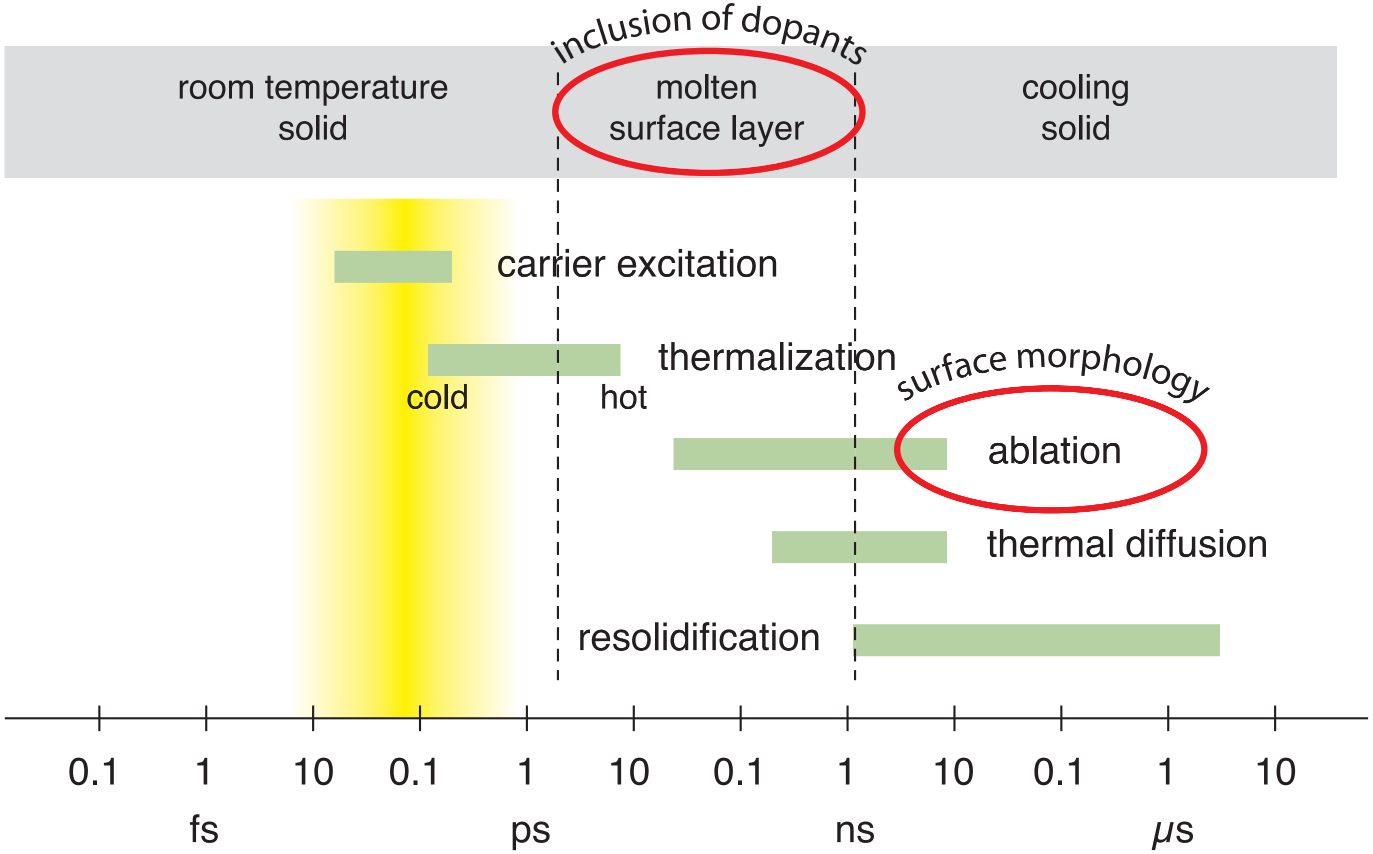


Structure

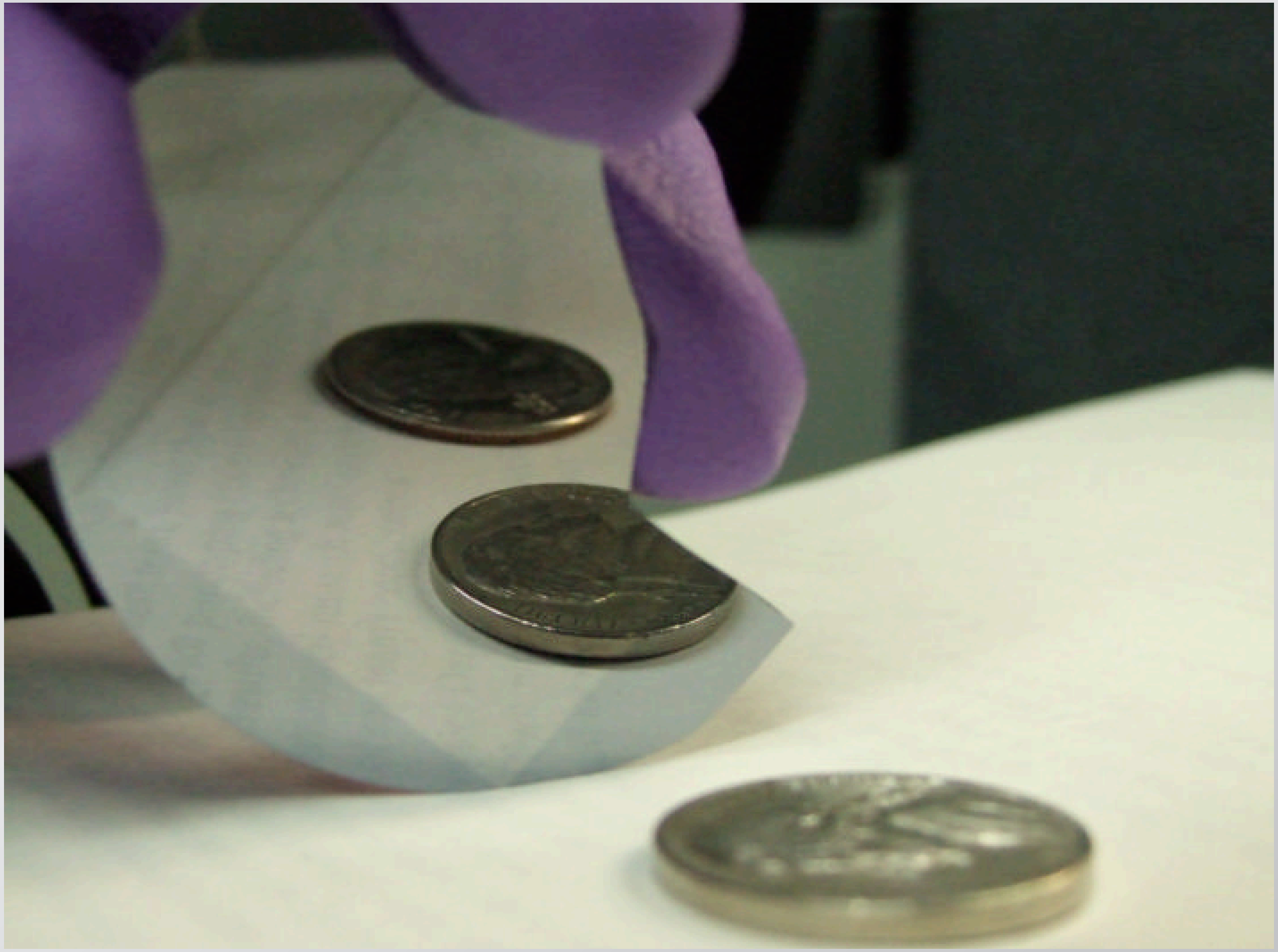
different thresholds:

melting: 1.5 kJ/m^2

ablation: 3.1 kJ/m^2

Structure

decouple ablation from melting



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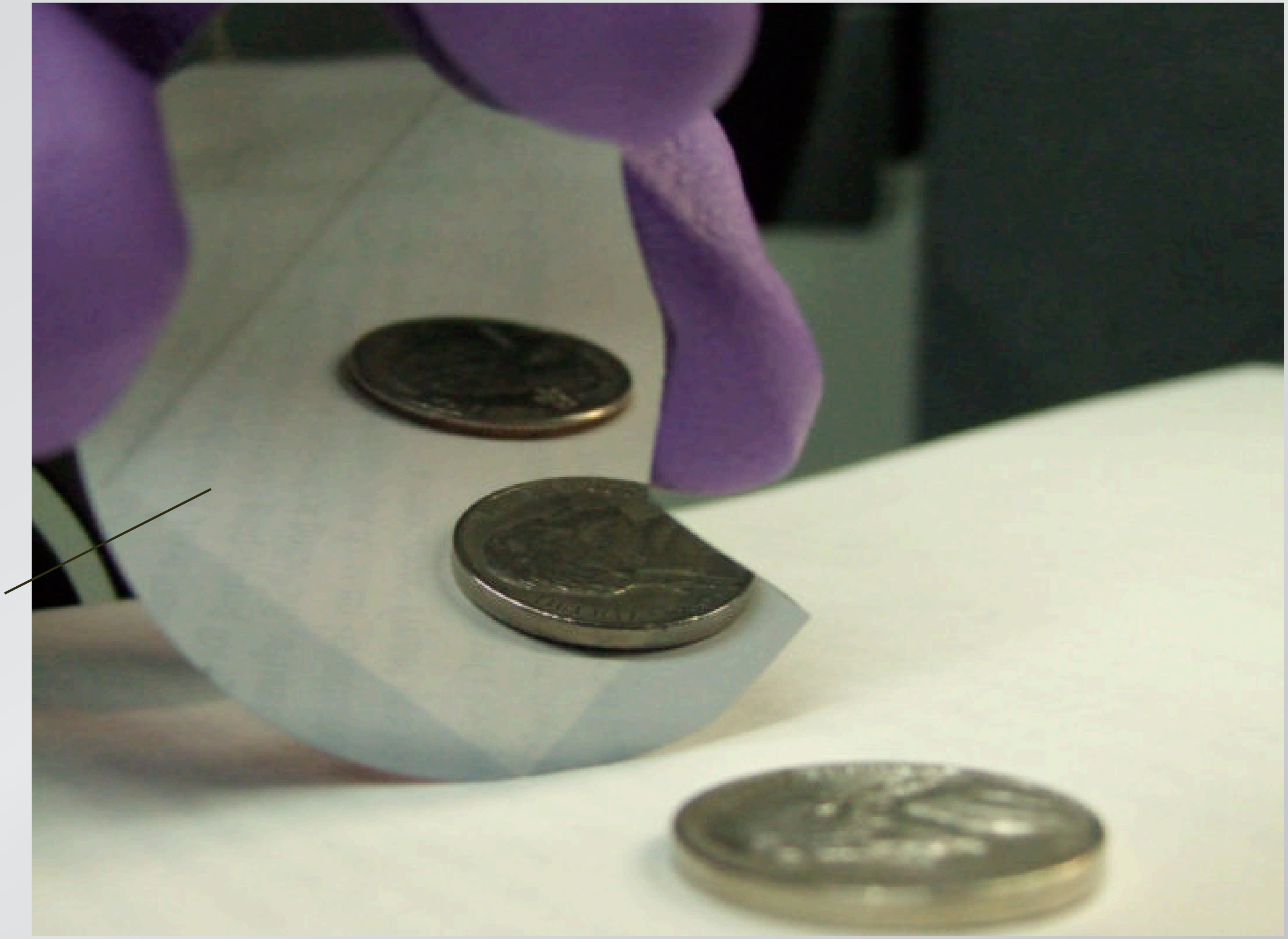

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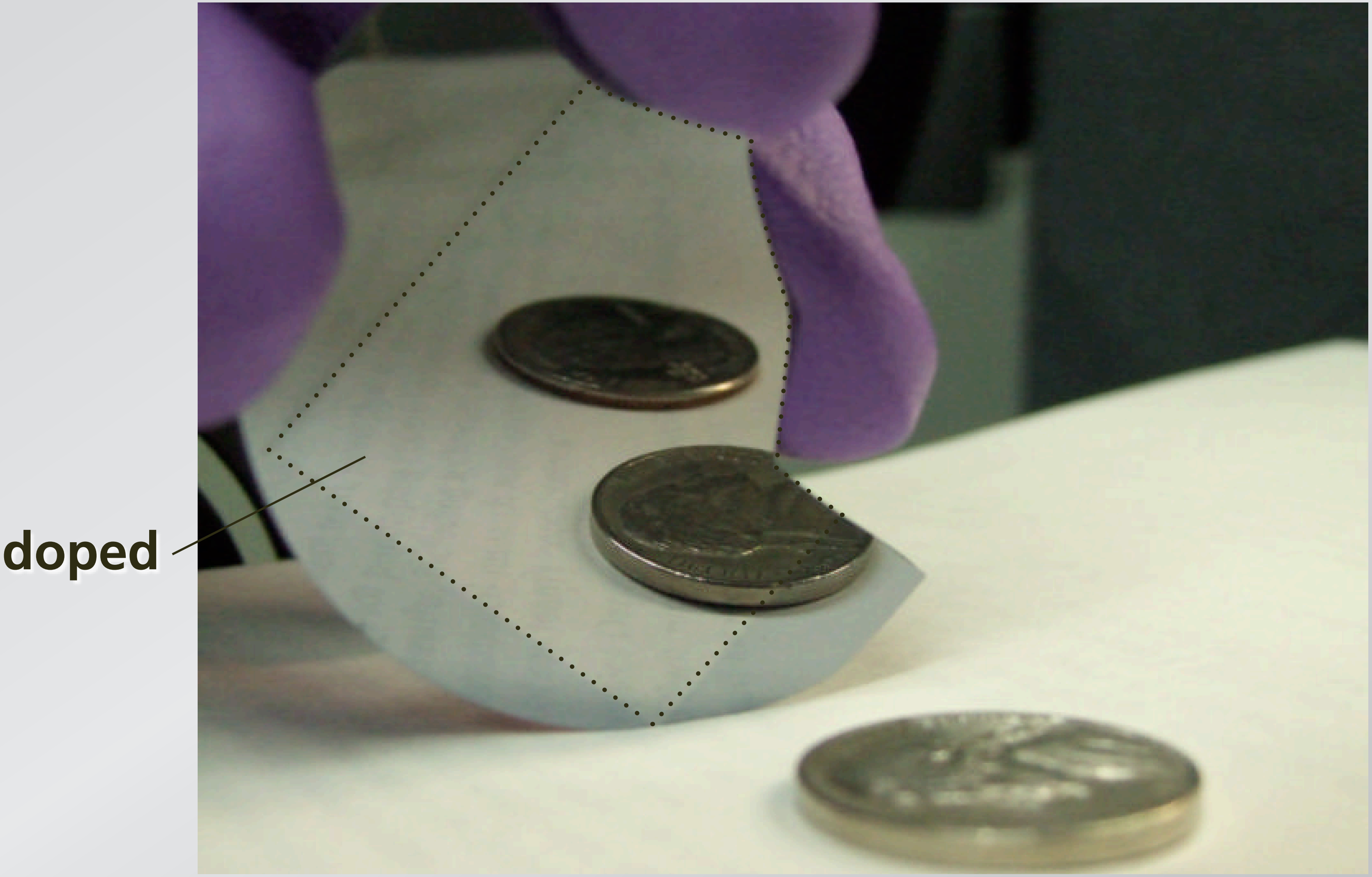

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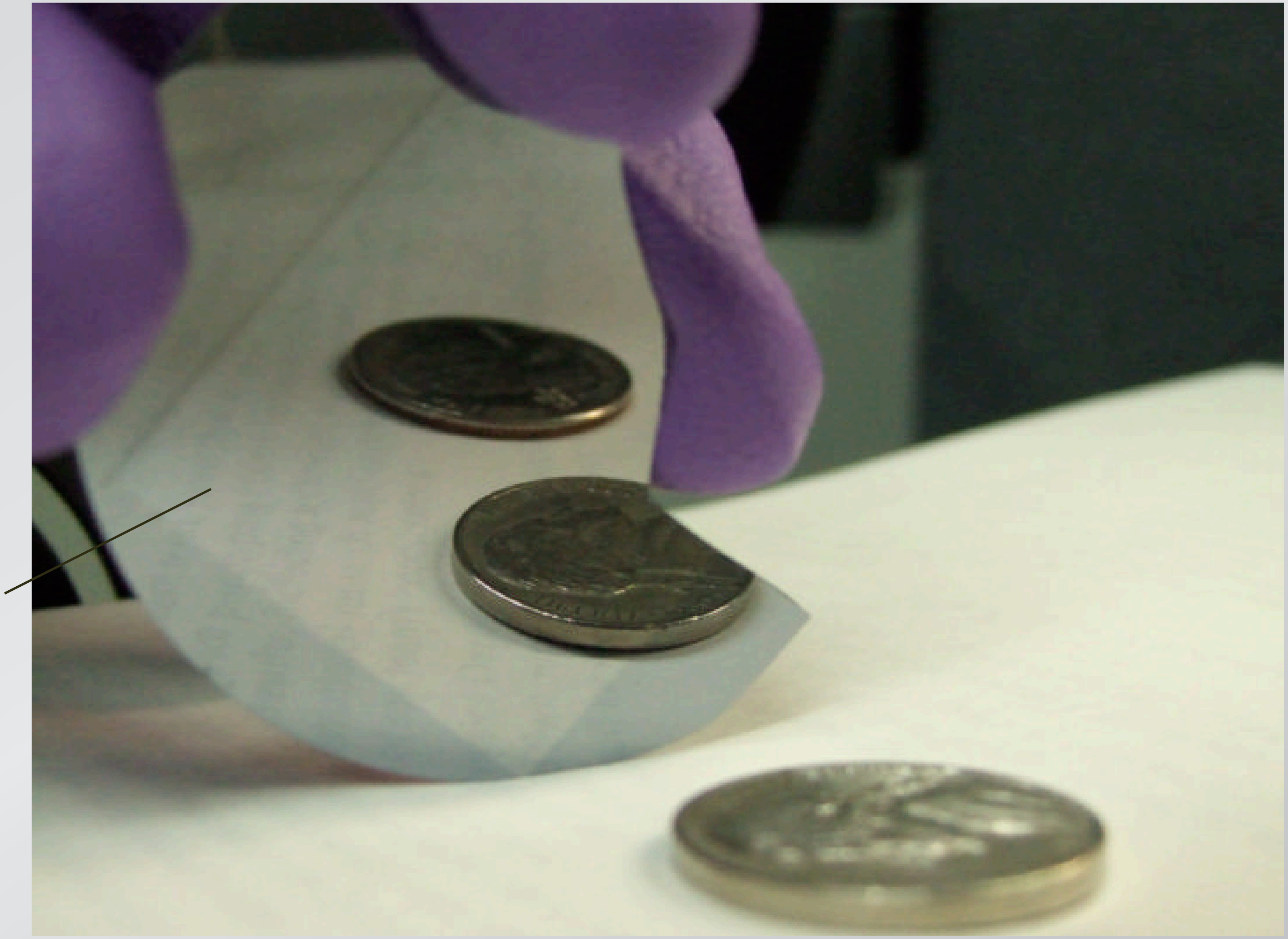

doped

Structure

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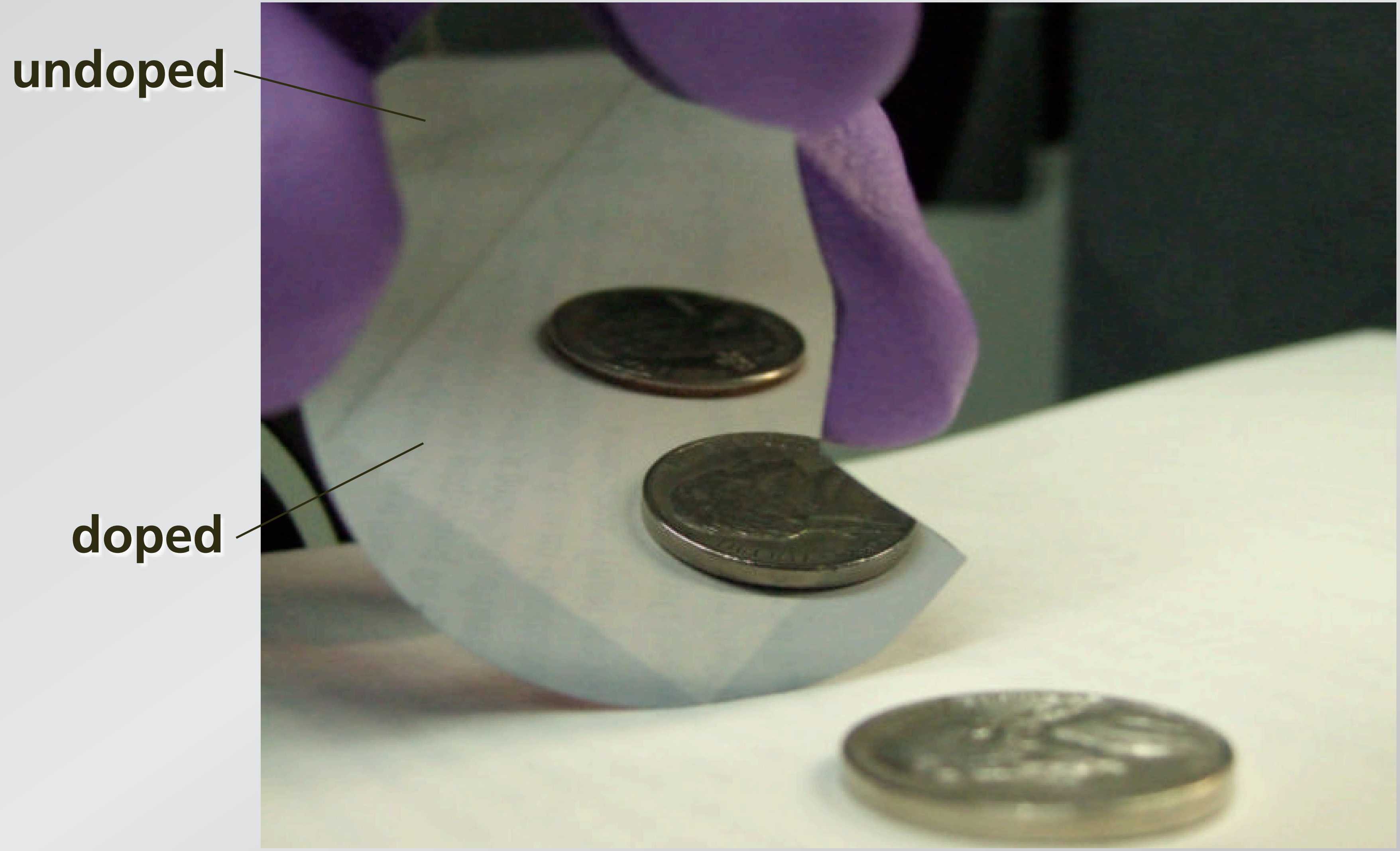

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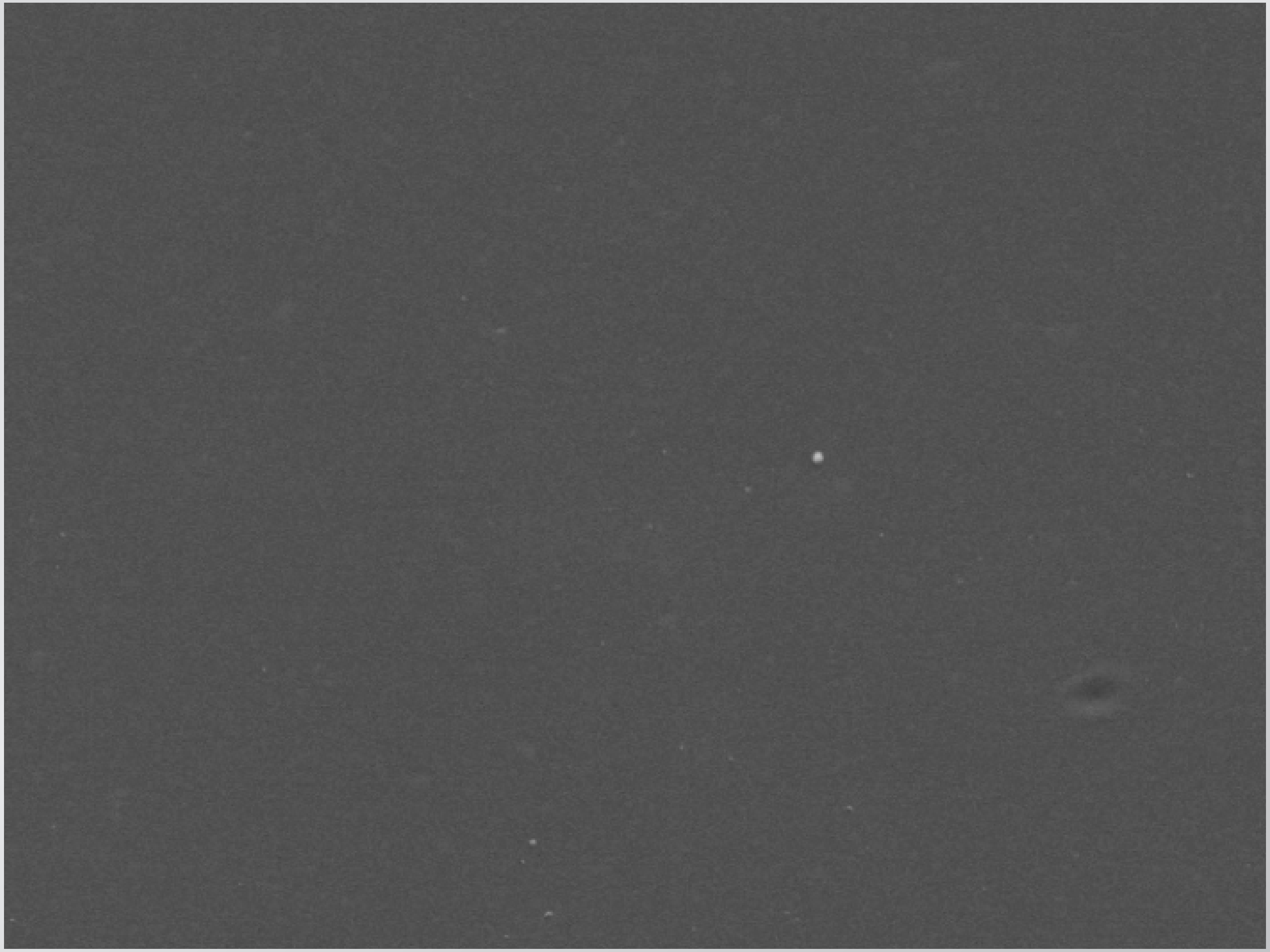

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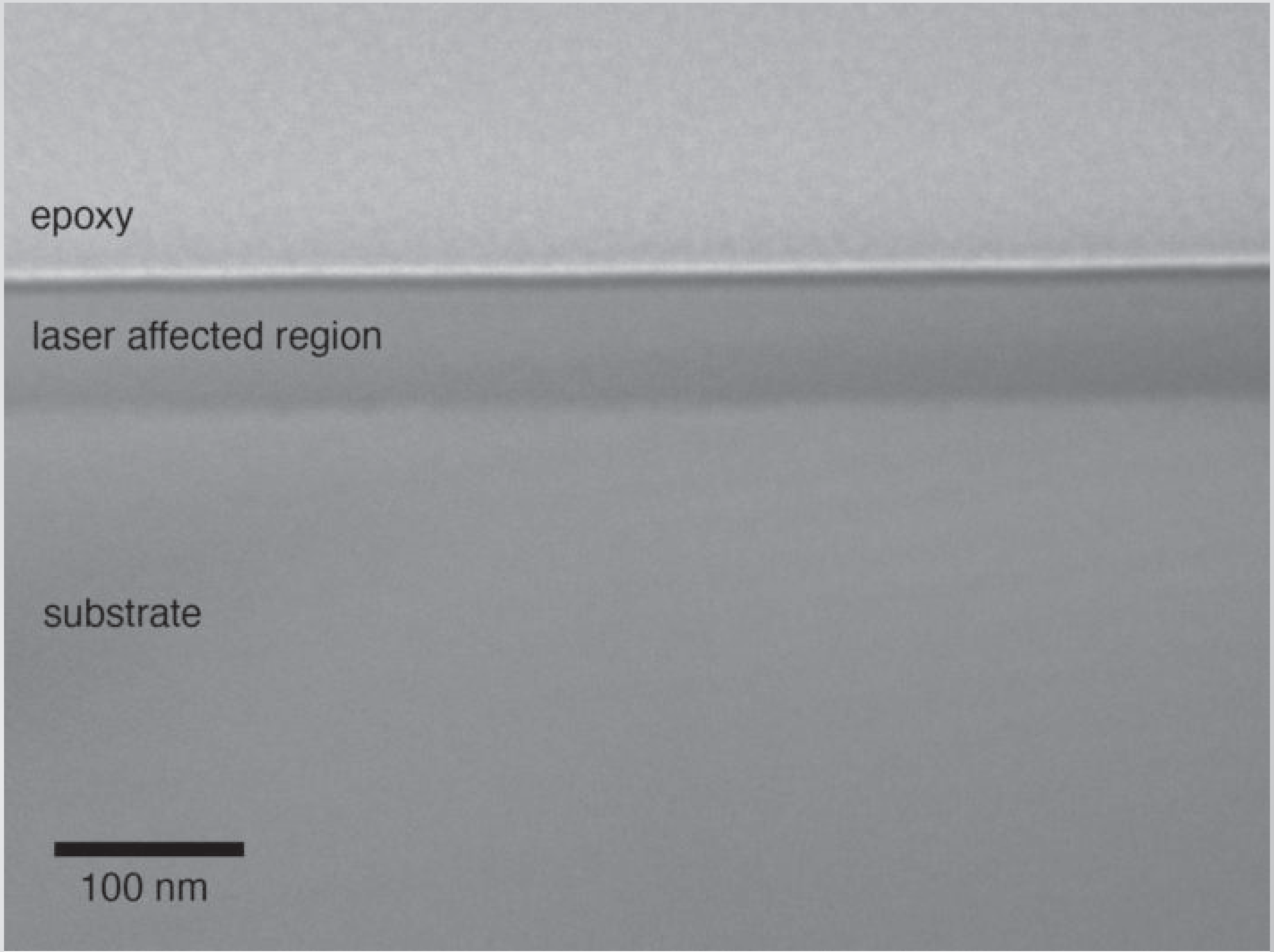

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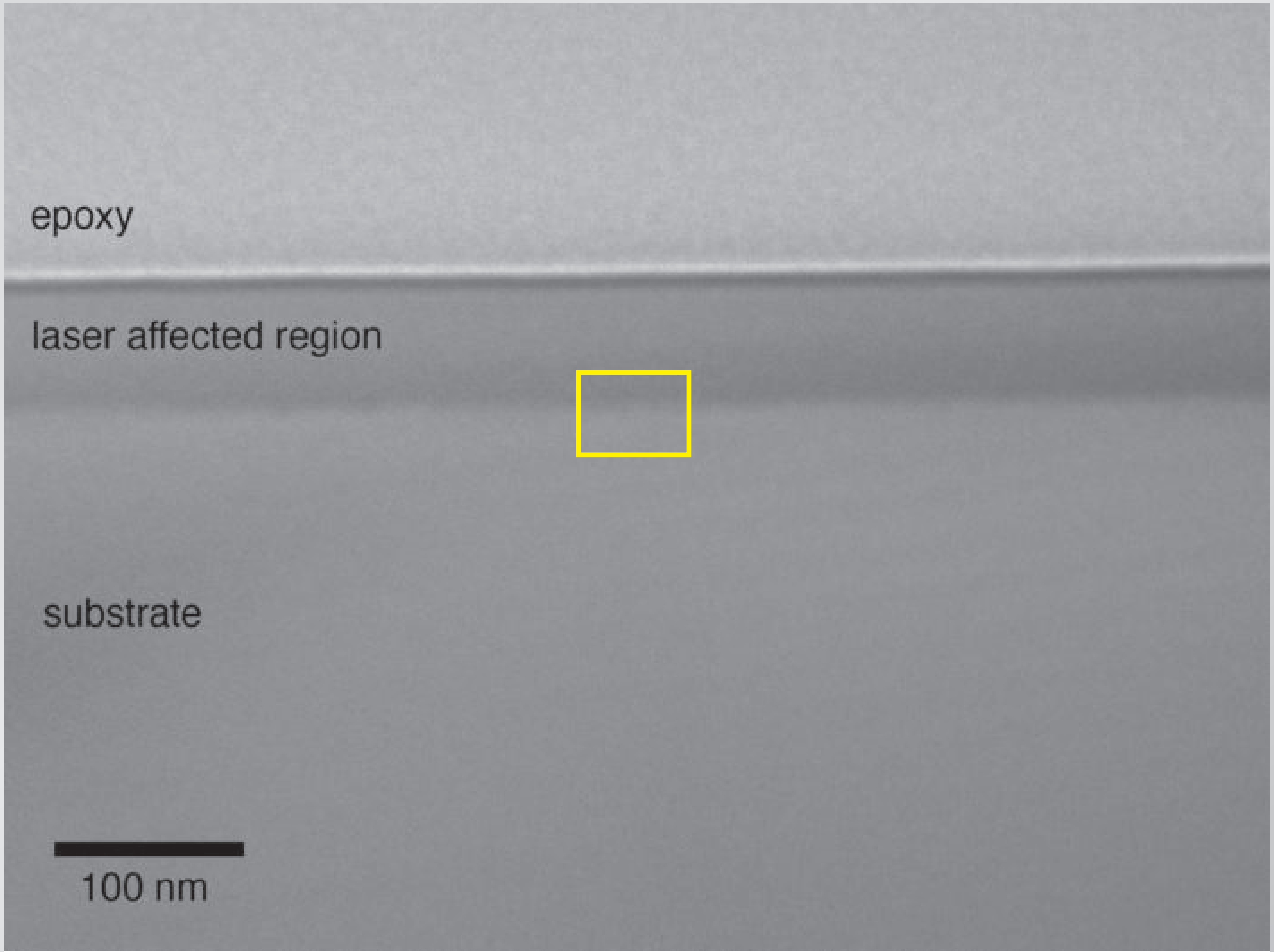

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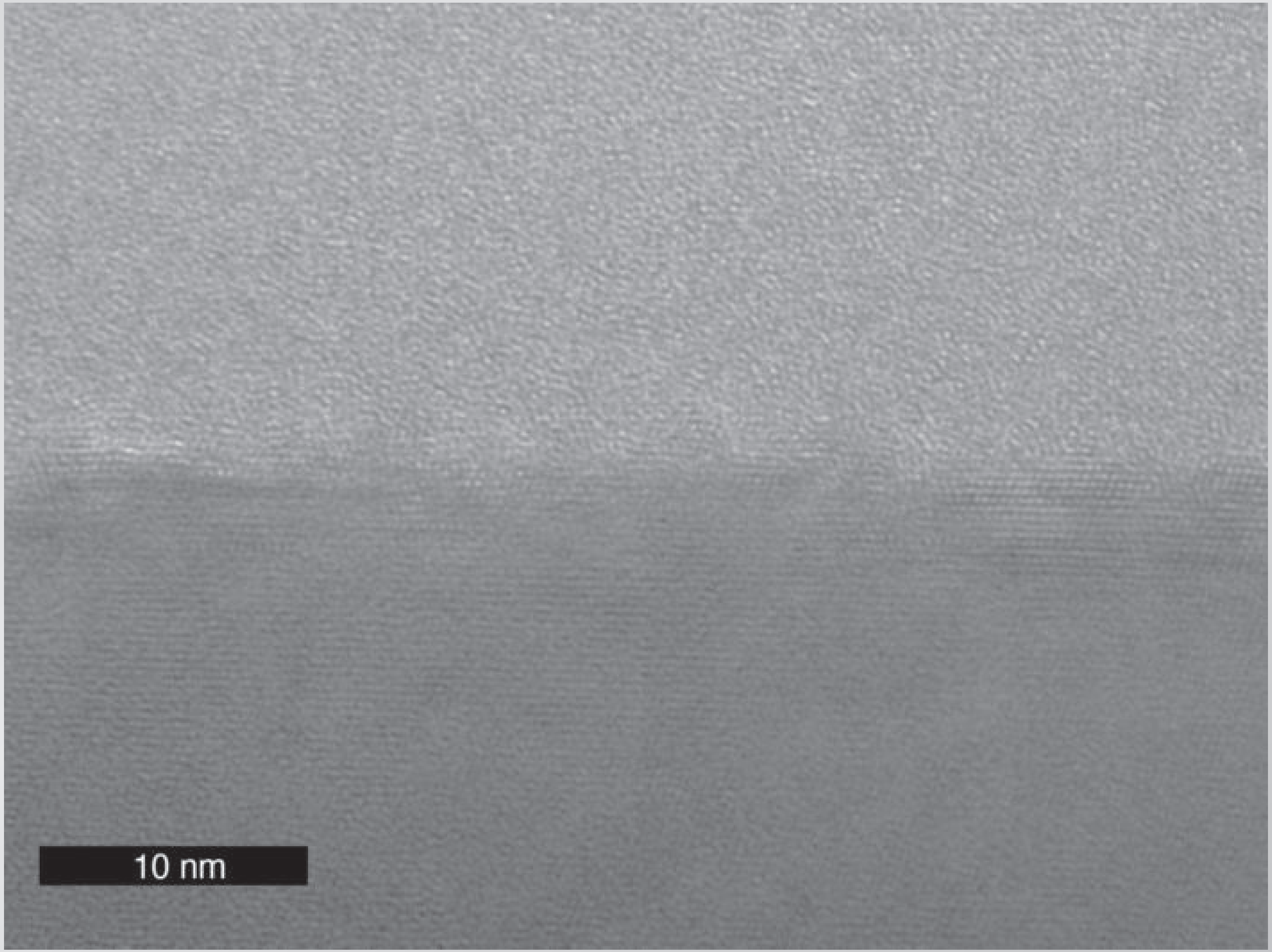

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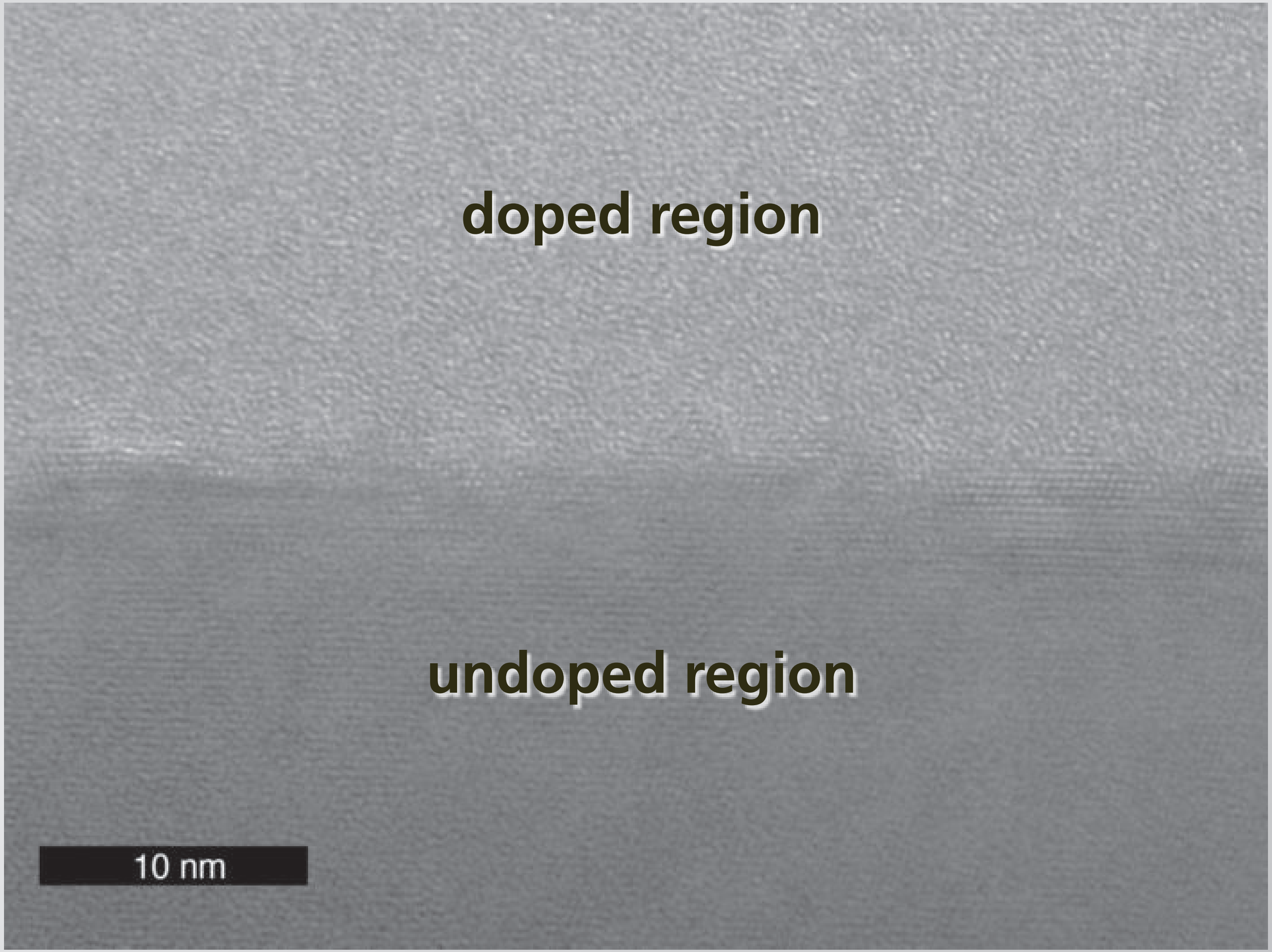

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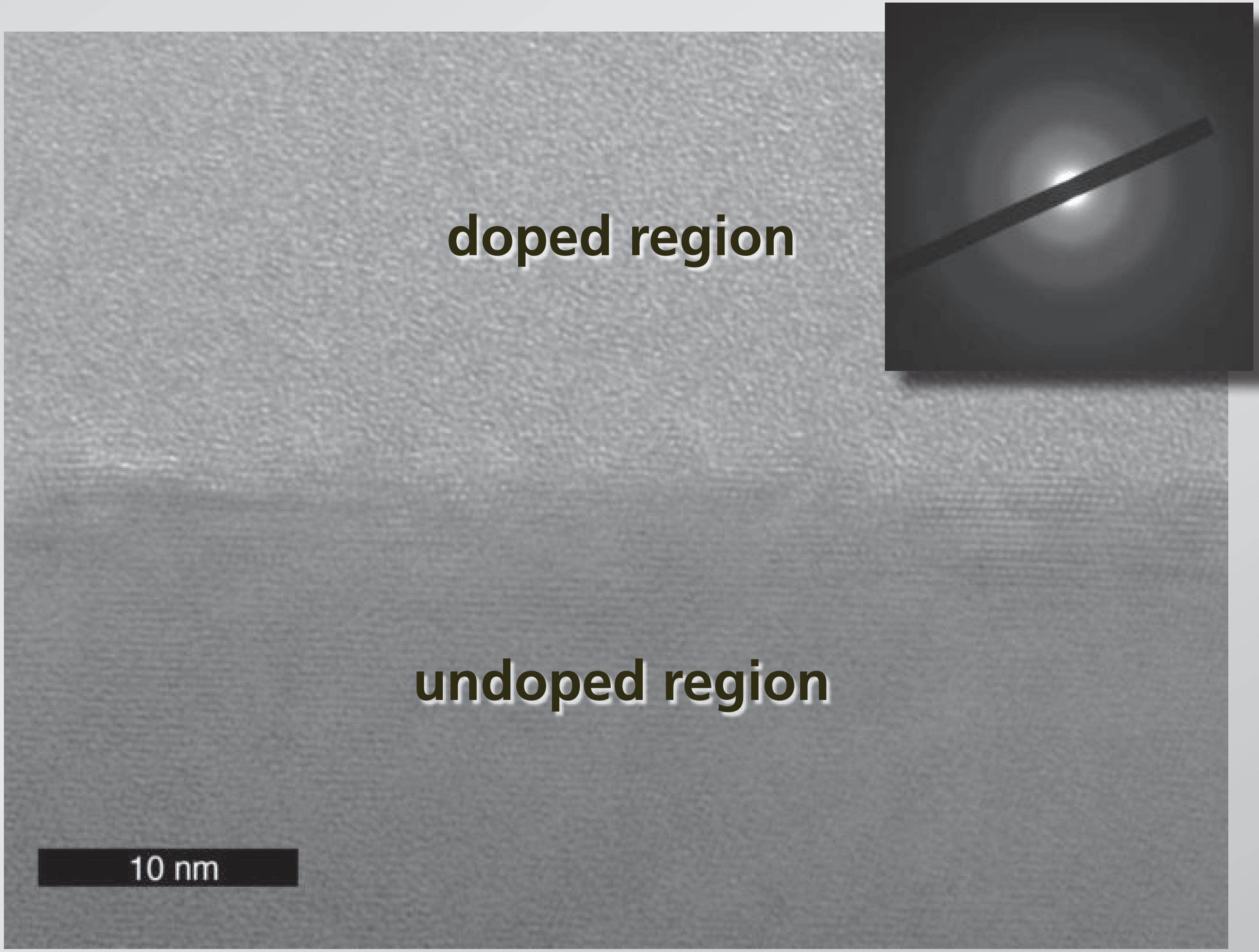
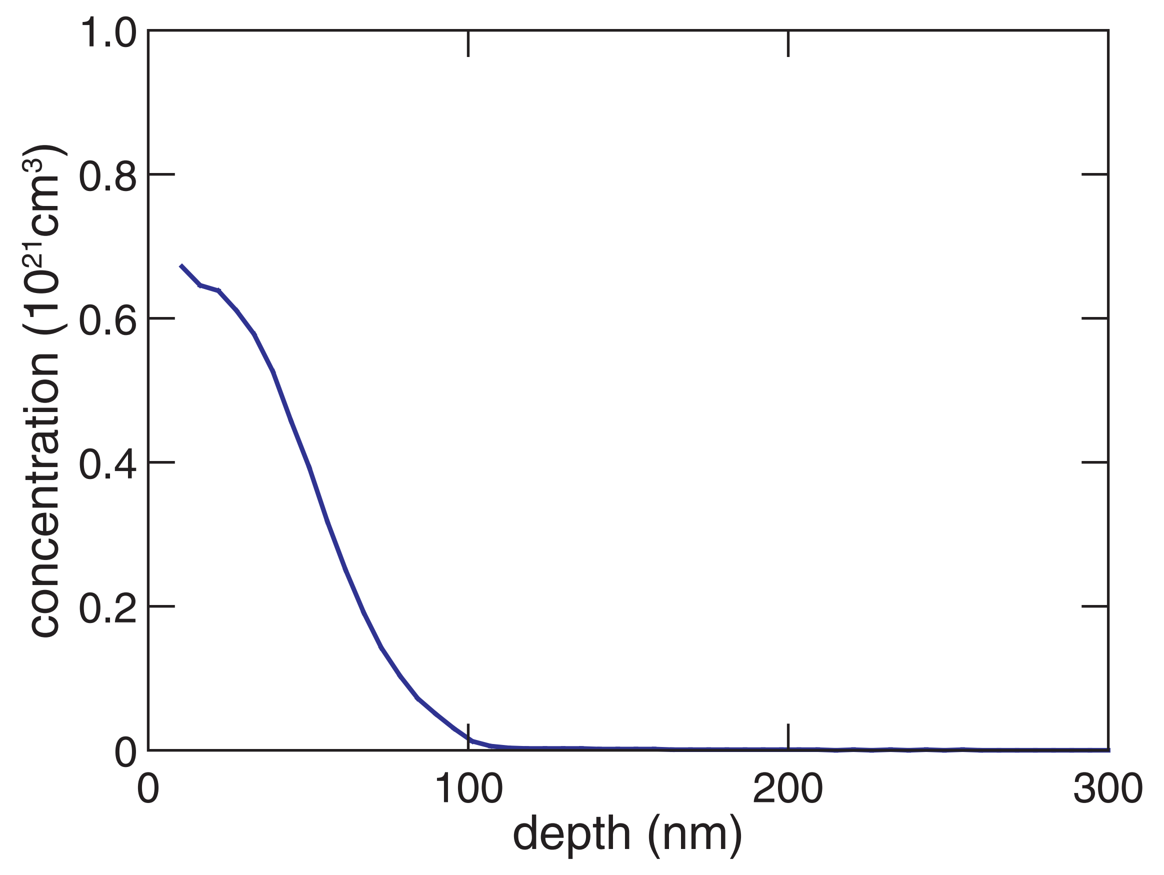


Structure

secondary ion mass spectrometry



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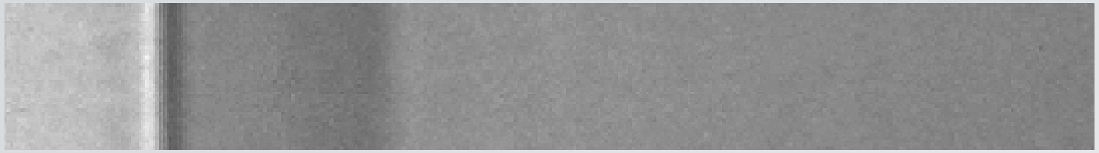
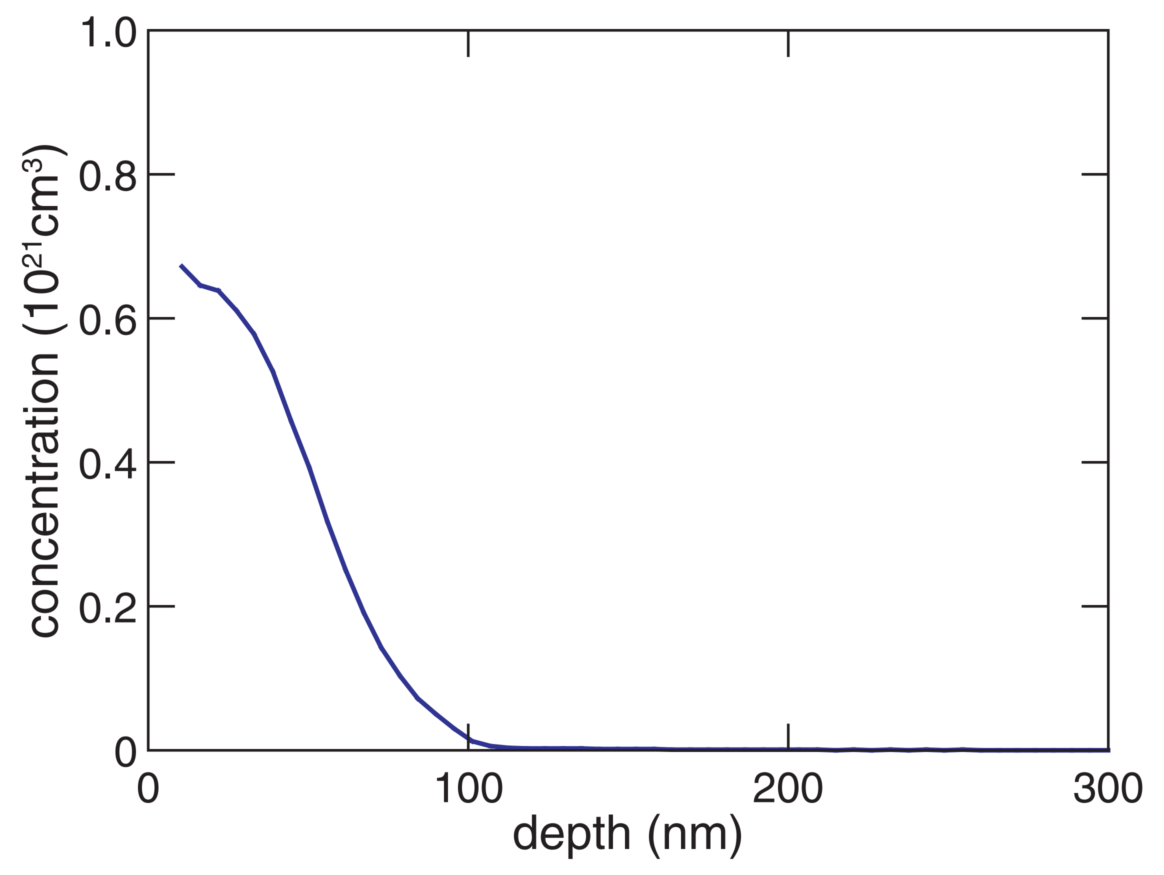




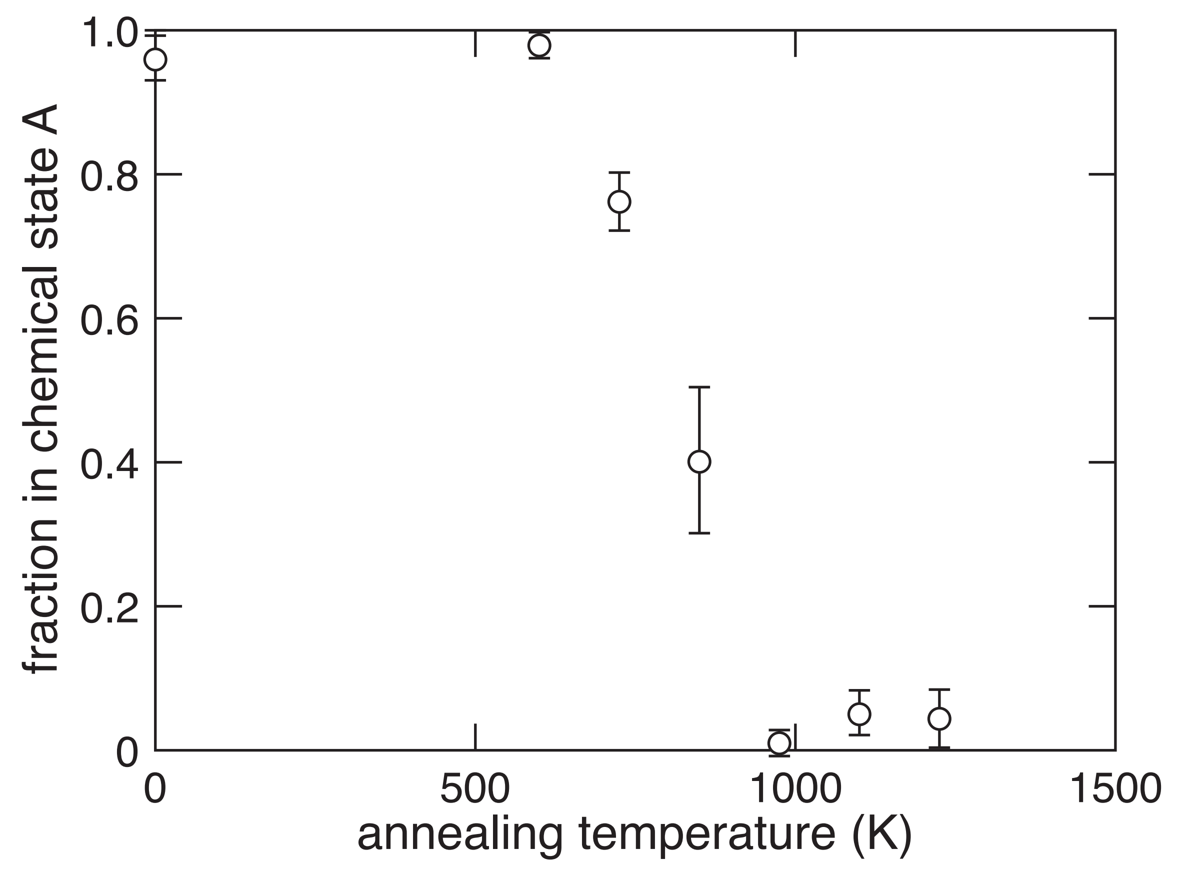
Structure

extended x-ray absorption fine structure spectrum:

dopant in two different chemical states

Structure

annealing changes local coordination



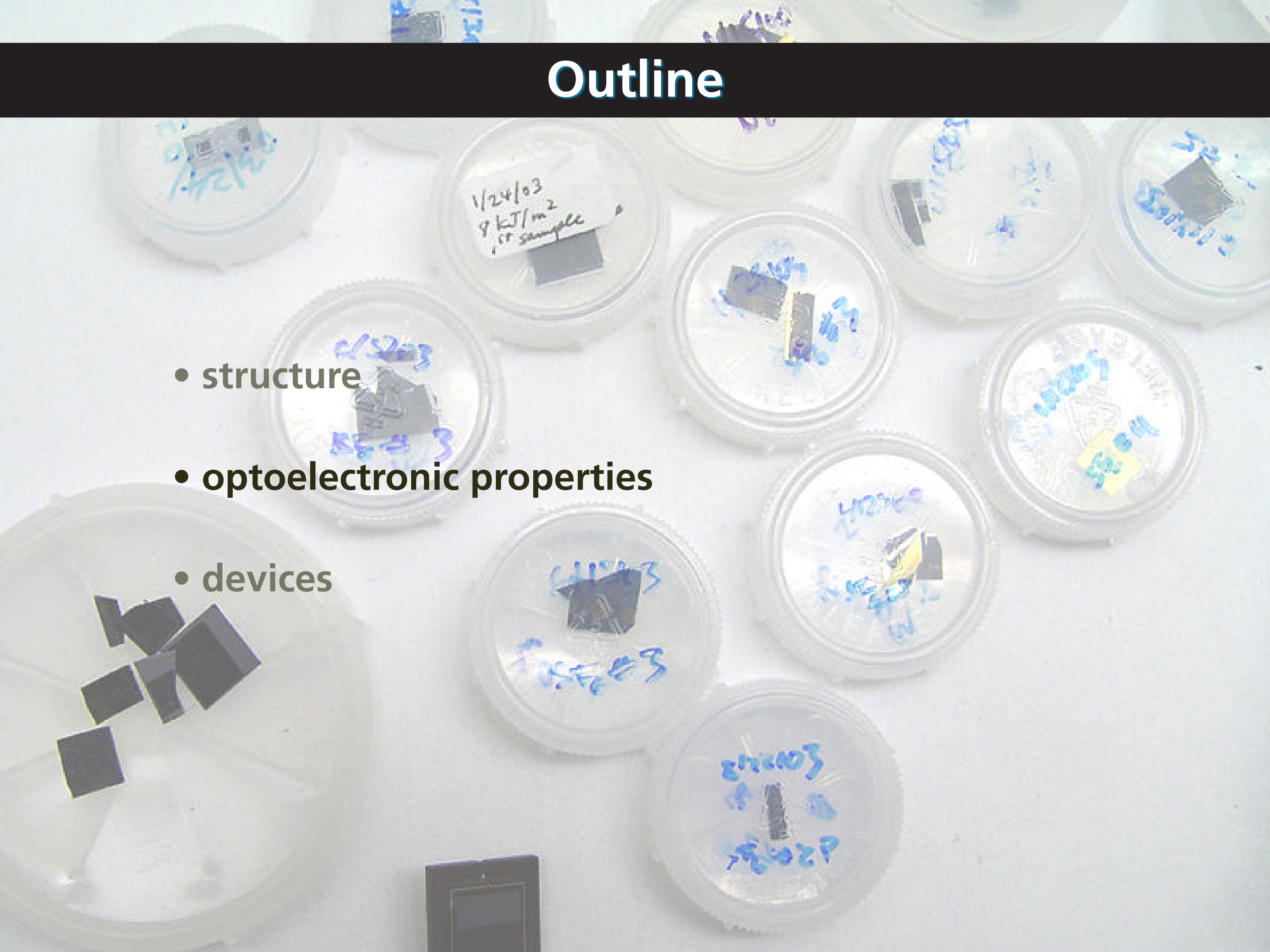
Buonassisi Group, MIT

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

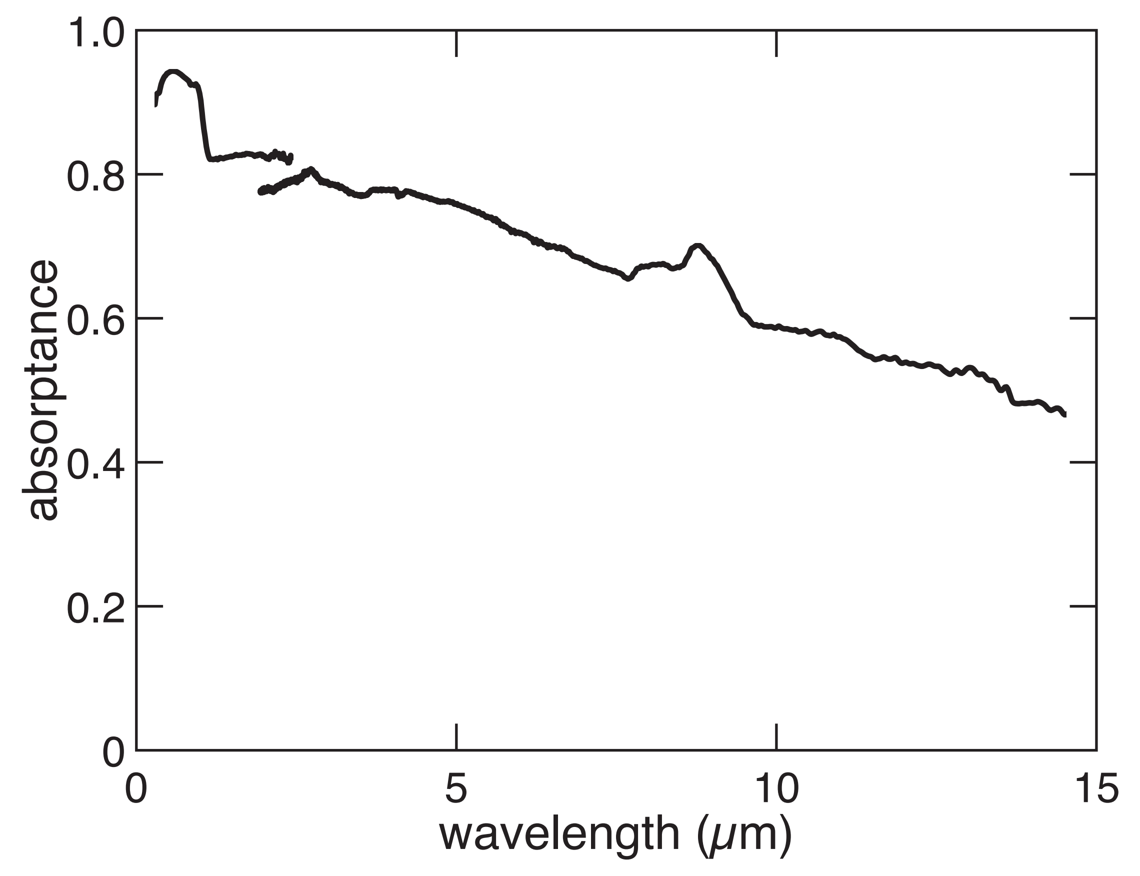
Outline



- structure
- optoelectronic properties
- devices

Optoelectronic properties

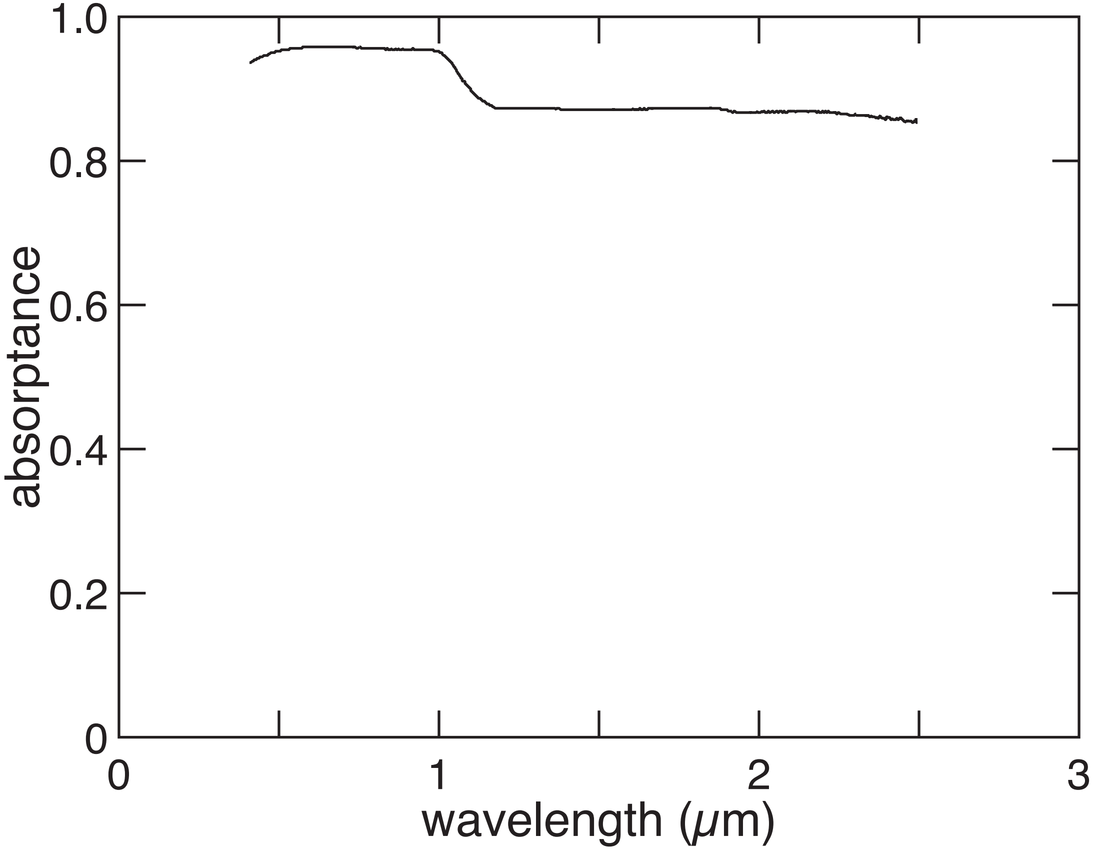
absorptance ($1 - R_{int} - T_{int}$)



Asenbaum, Vienna

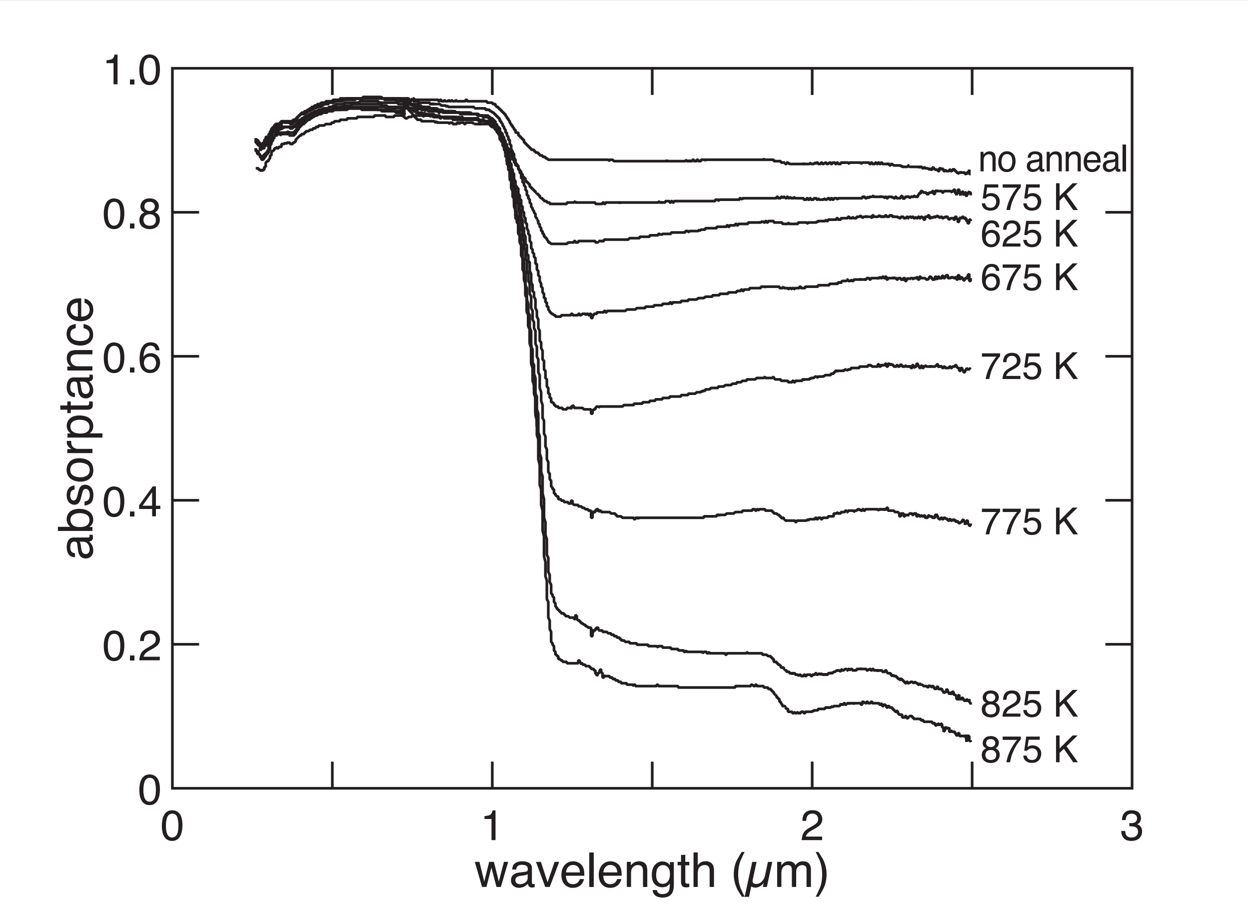
Optoelectronic properties

effect of annealing on IR absorptance



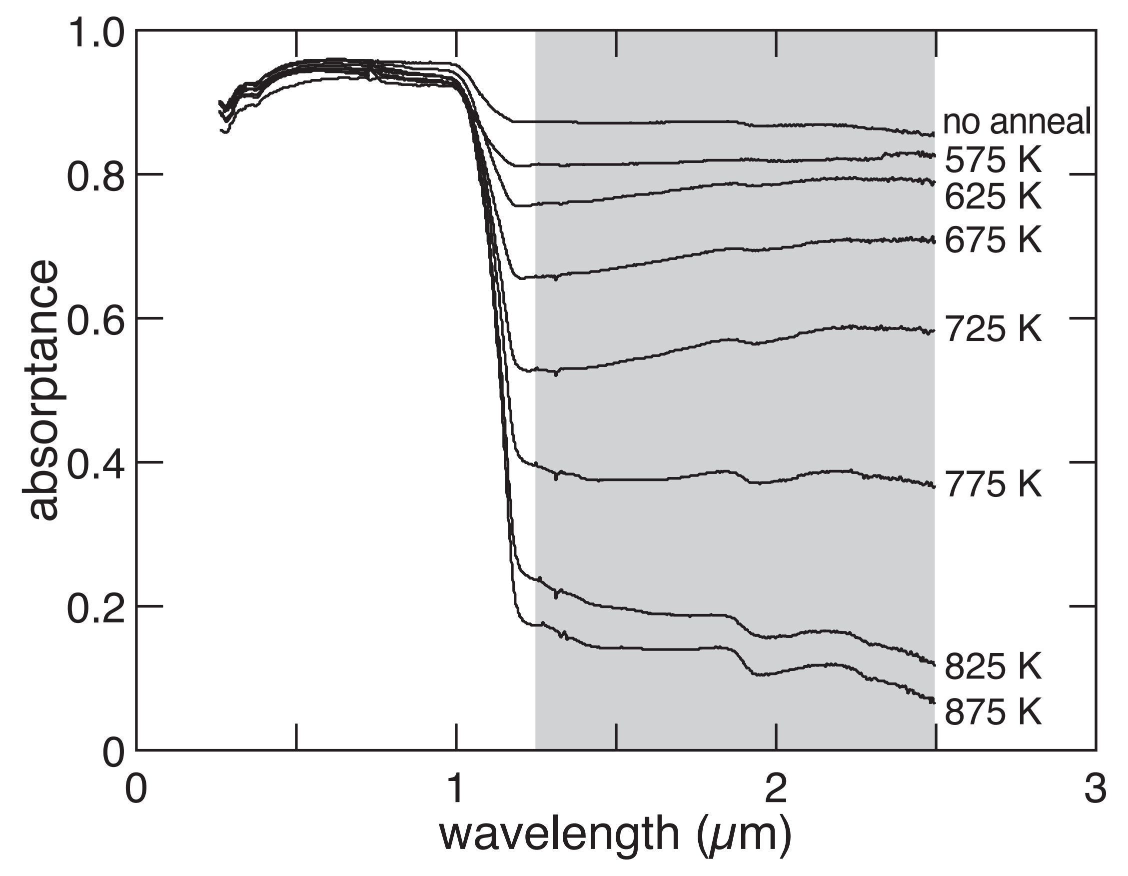
Optoelectronic properties

effect of annealing on IR absorptance



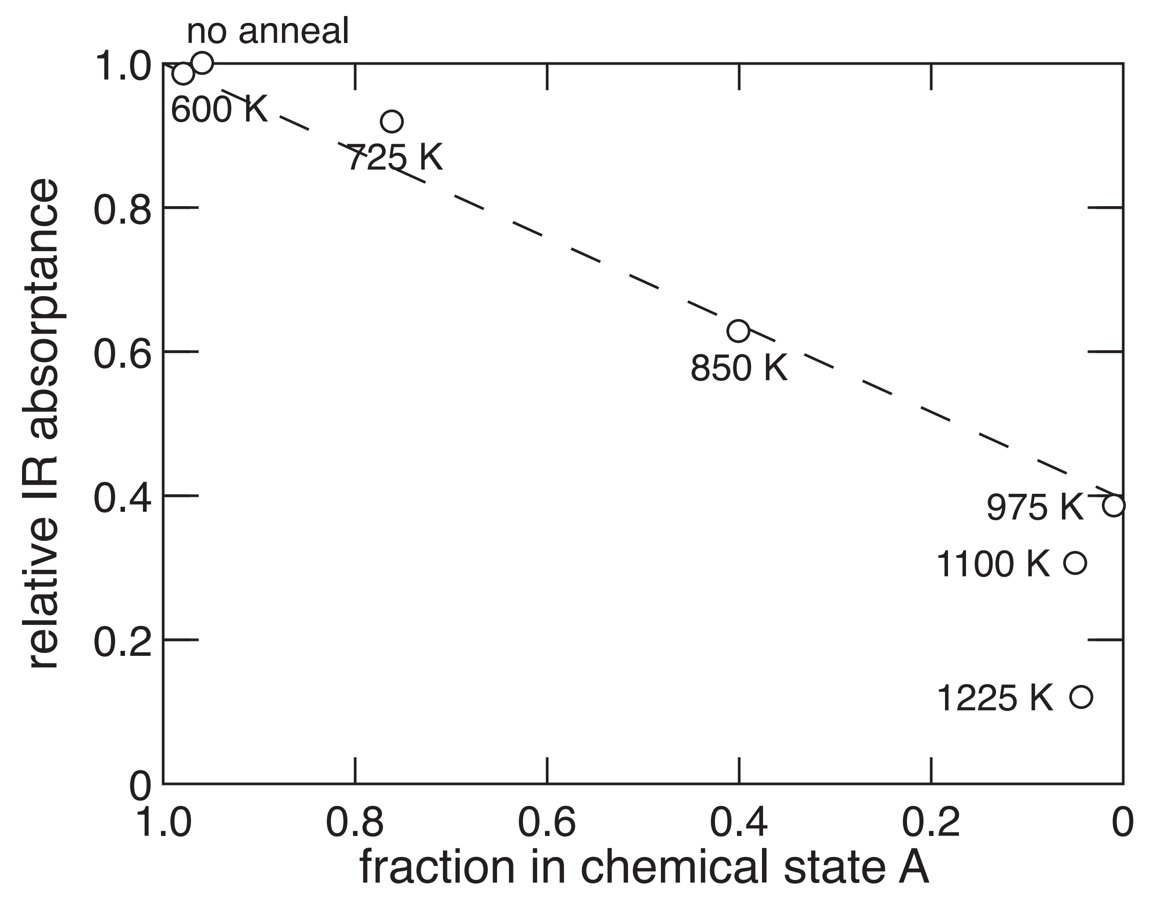
Optoelectronic properties

effect of annealing on IR absorptance



Optoelectronic properties

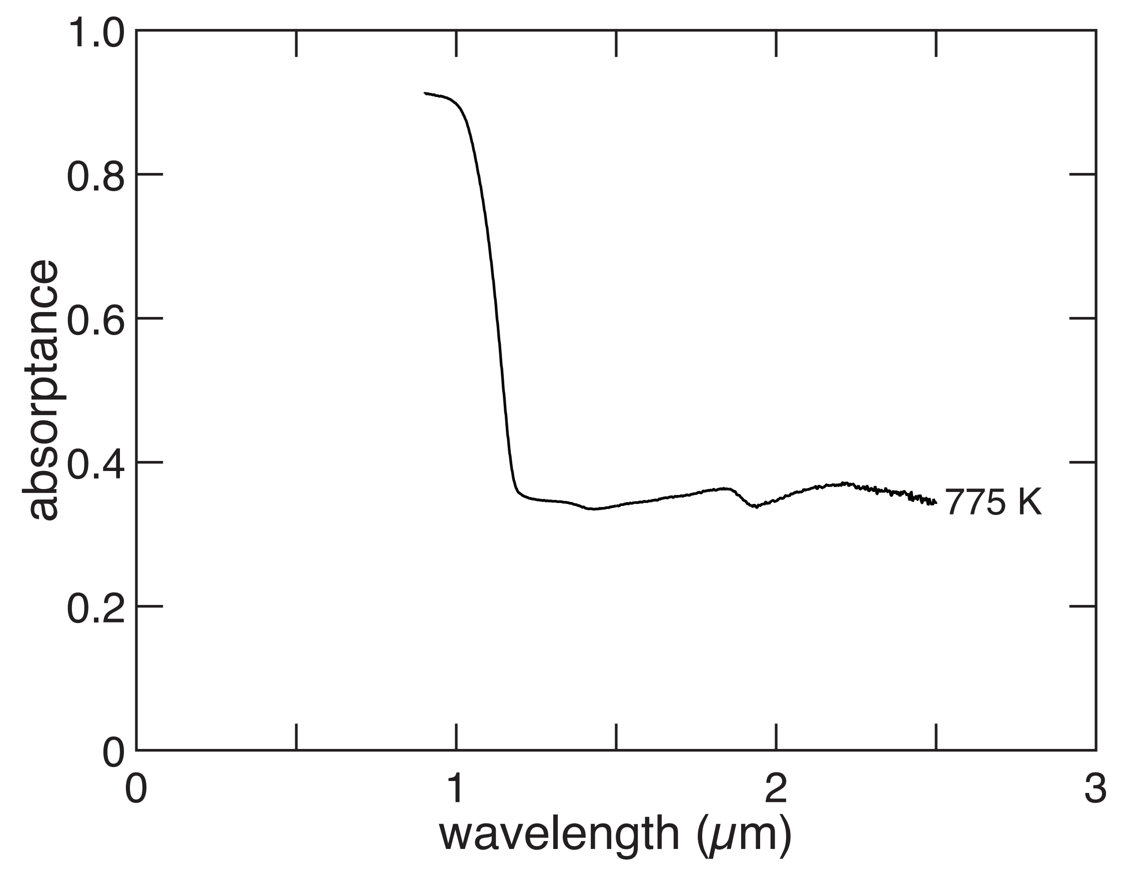
correlates with recoordination observed in EXAFS



Buonassisi Group, MIT

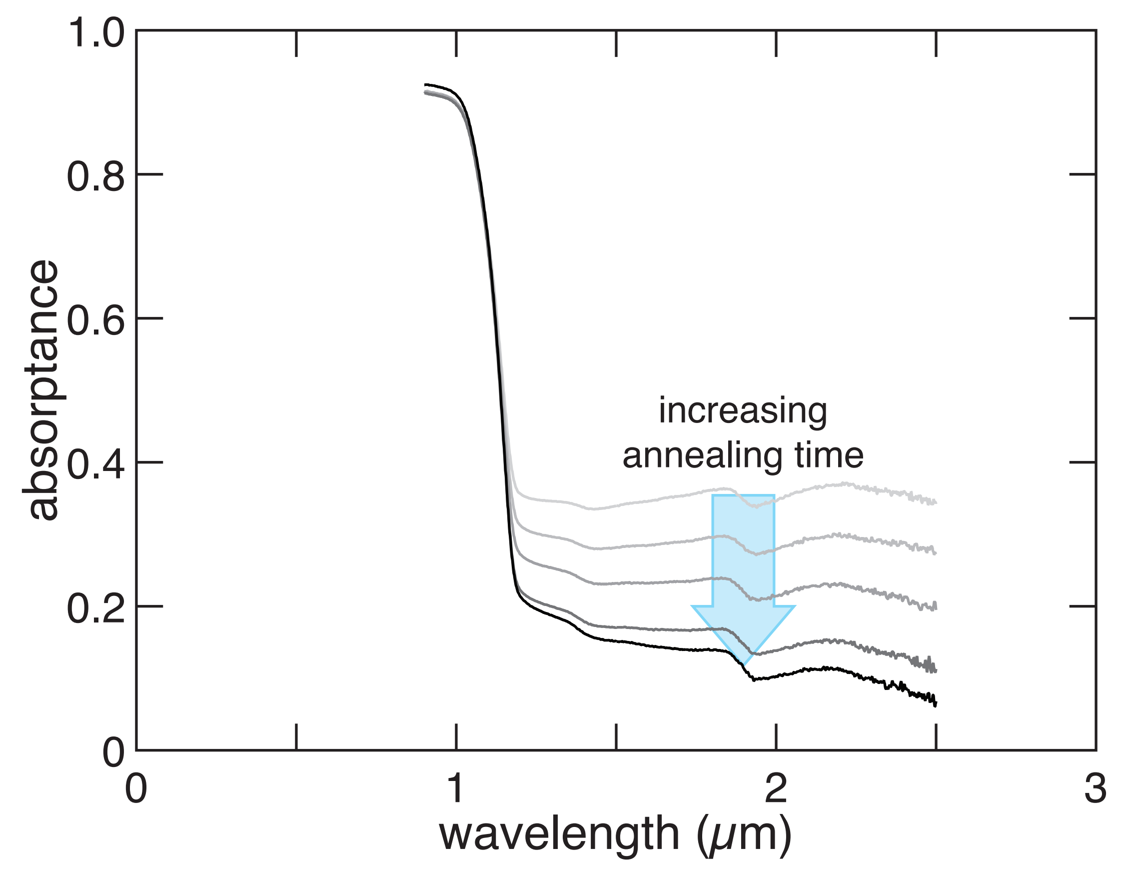
Optoelectronic properties

vary annealing time



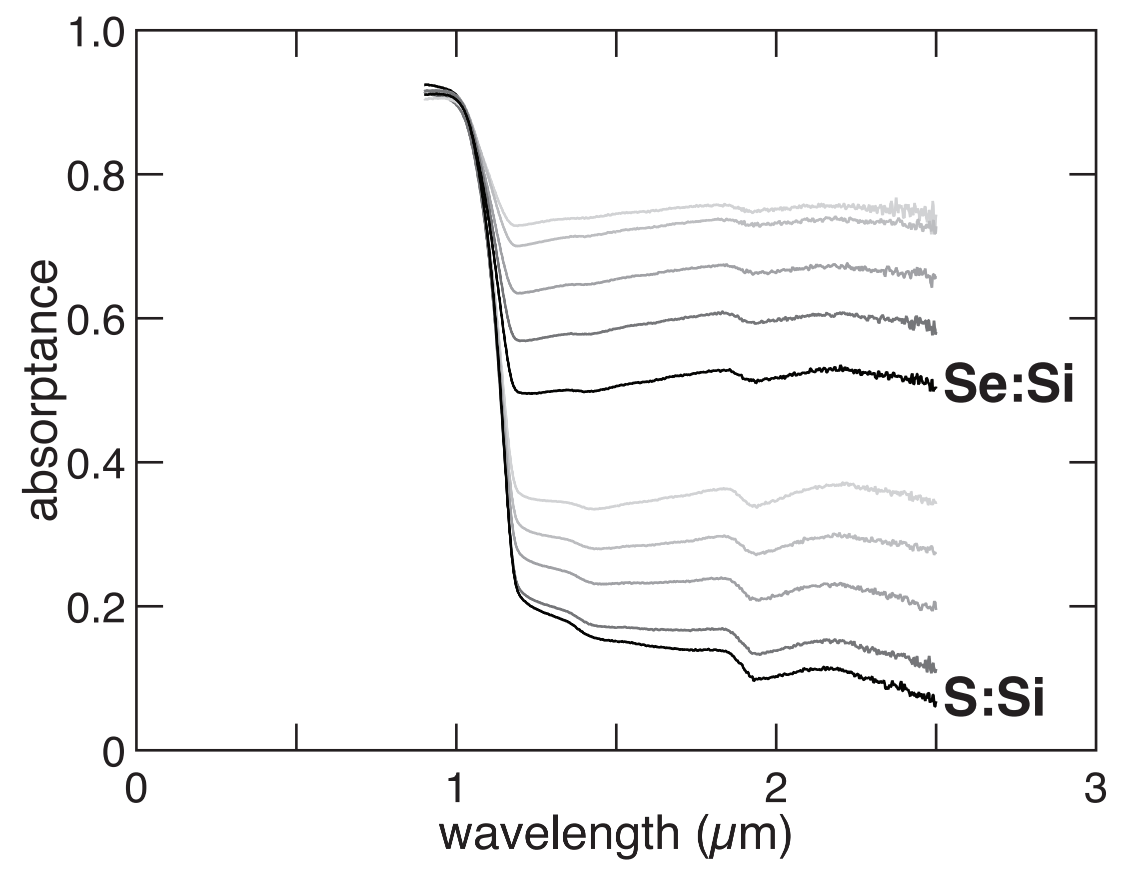
Optoelectronic properties

longer annealing decreases IR absorptance



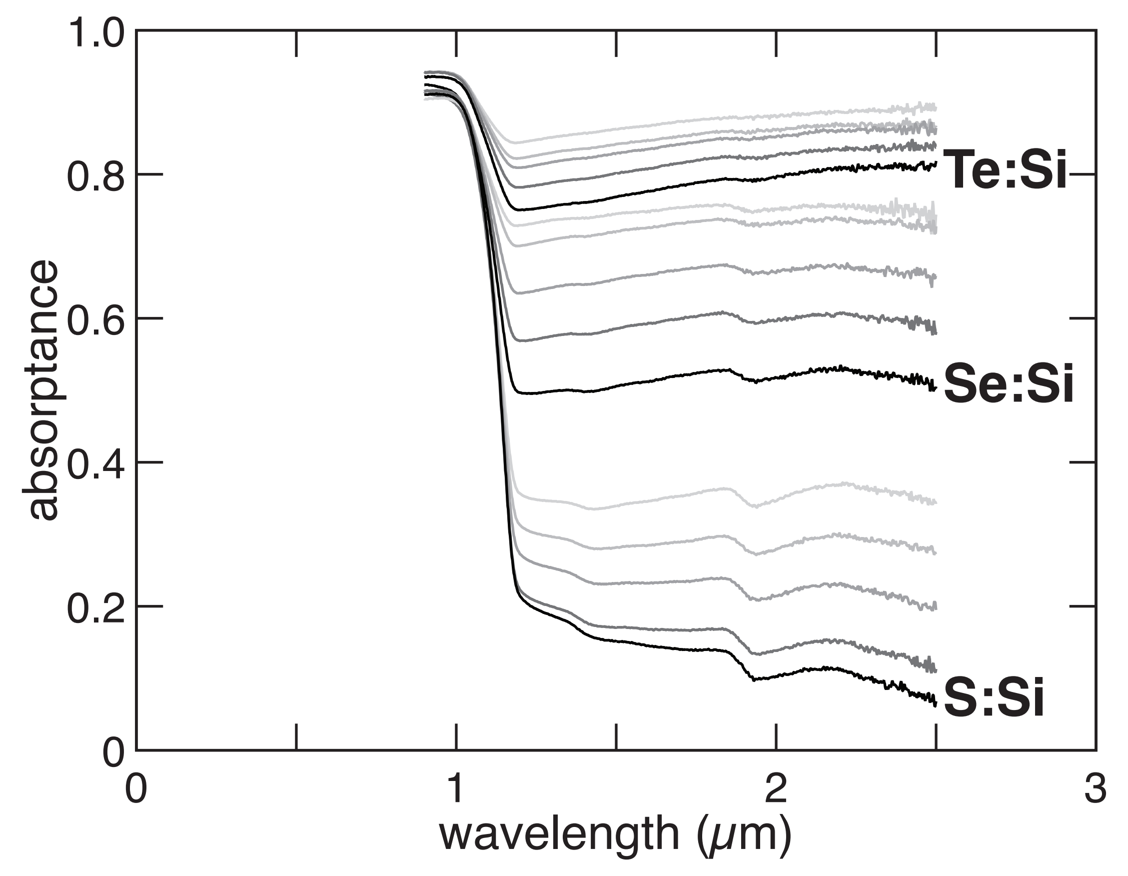
Optoelectronic properties

IR absorptance decreases less for Se-doped samples…



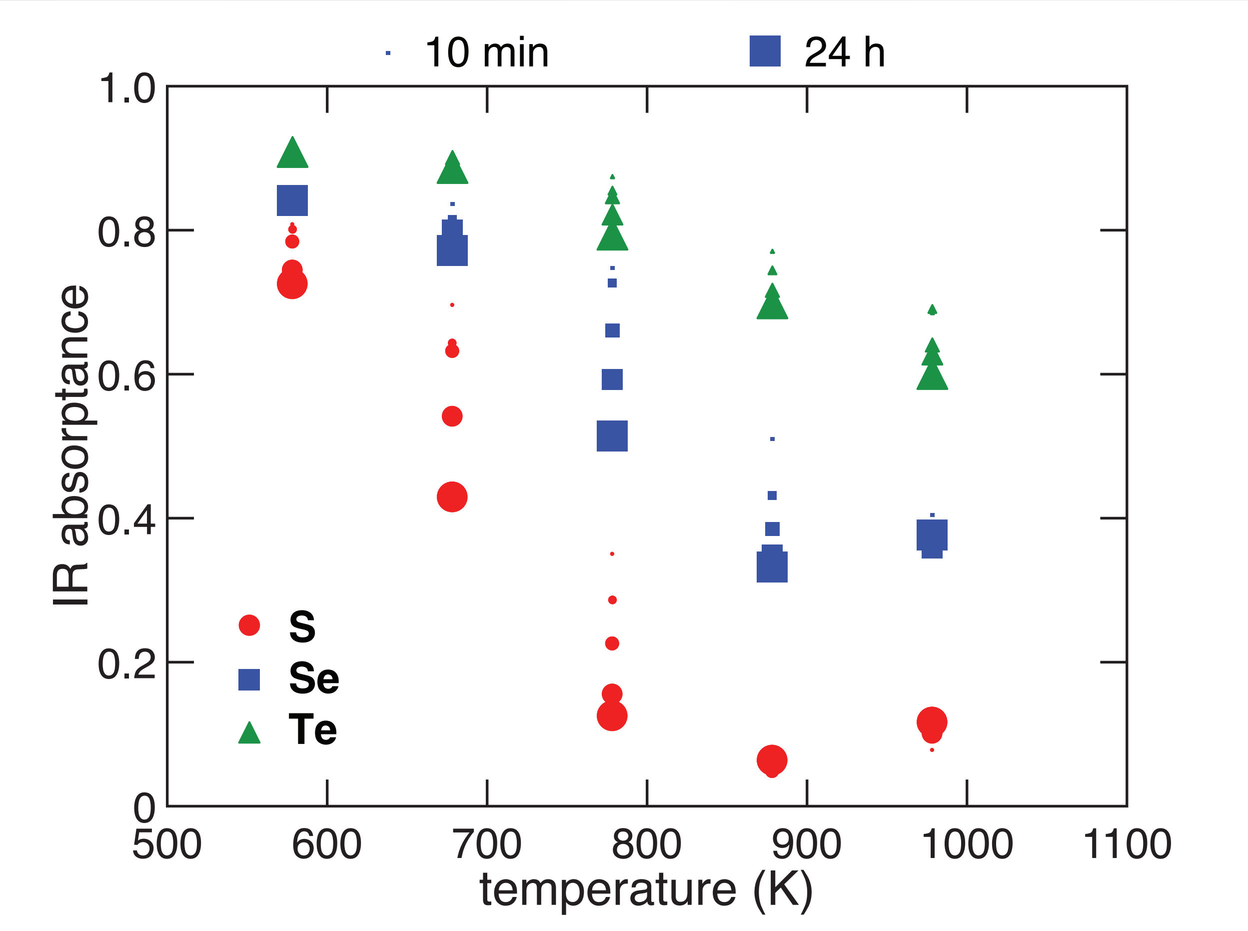
Optoelectronic properties

and even less for Te-doped samples…



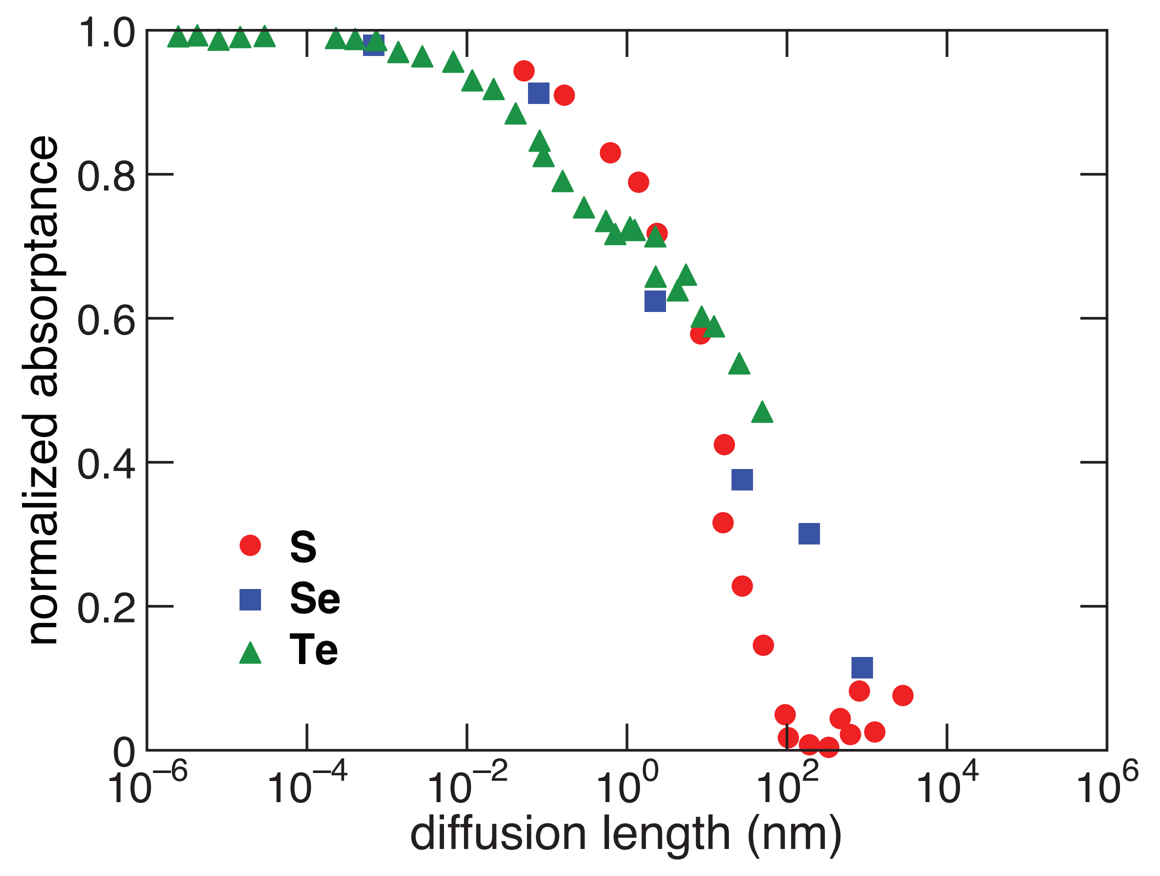
Optoelectronic properties

IR absorptance function of species, T_{anneal}, and t_{anneal}…



Optoelectronic properties

…but is unique function of diffusion length



Optoelectronic properties

annealing…

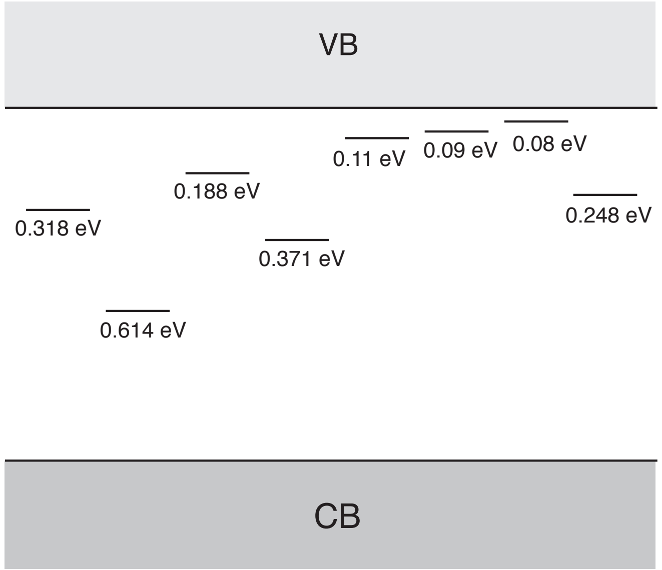
- decreases IR absorptance
- causes recoordination and diffusion of dopants
- IR absorptance reduced by 50% after 20 nm diffusion

Optoelectronic properties

what dopant states/bands cause IR absorption?

Optoelectronic properties

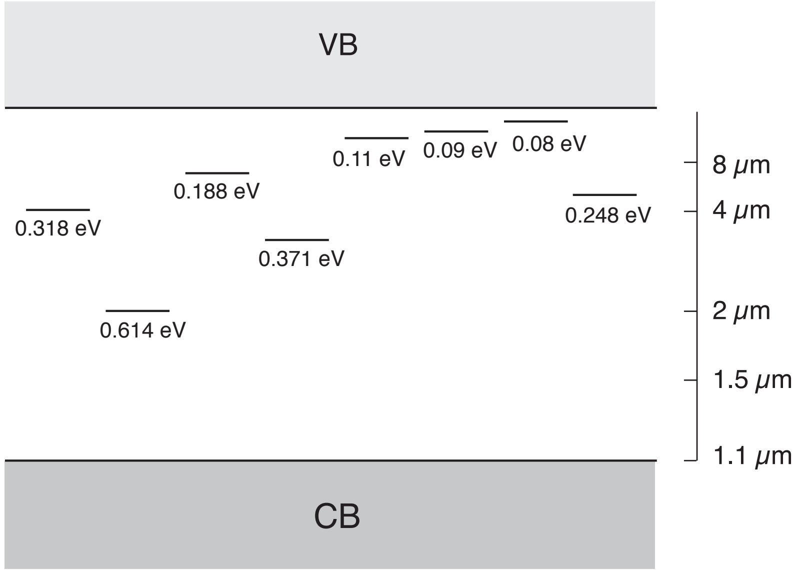
1 part in 10^6 sulfur introduces donor states in gap



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

Optoelectronic properties

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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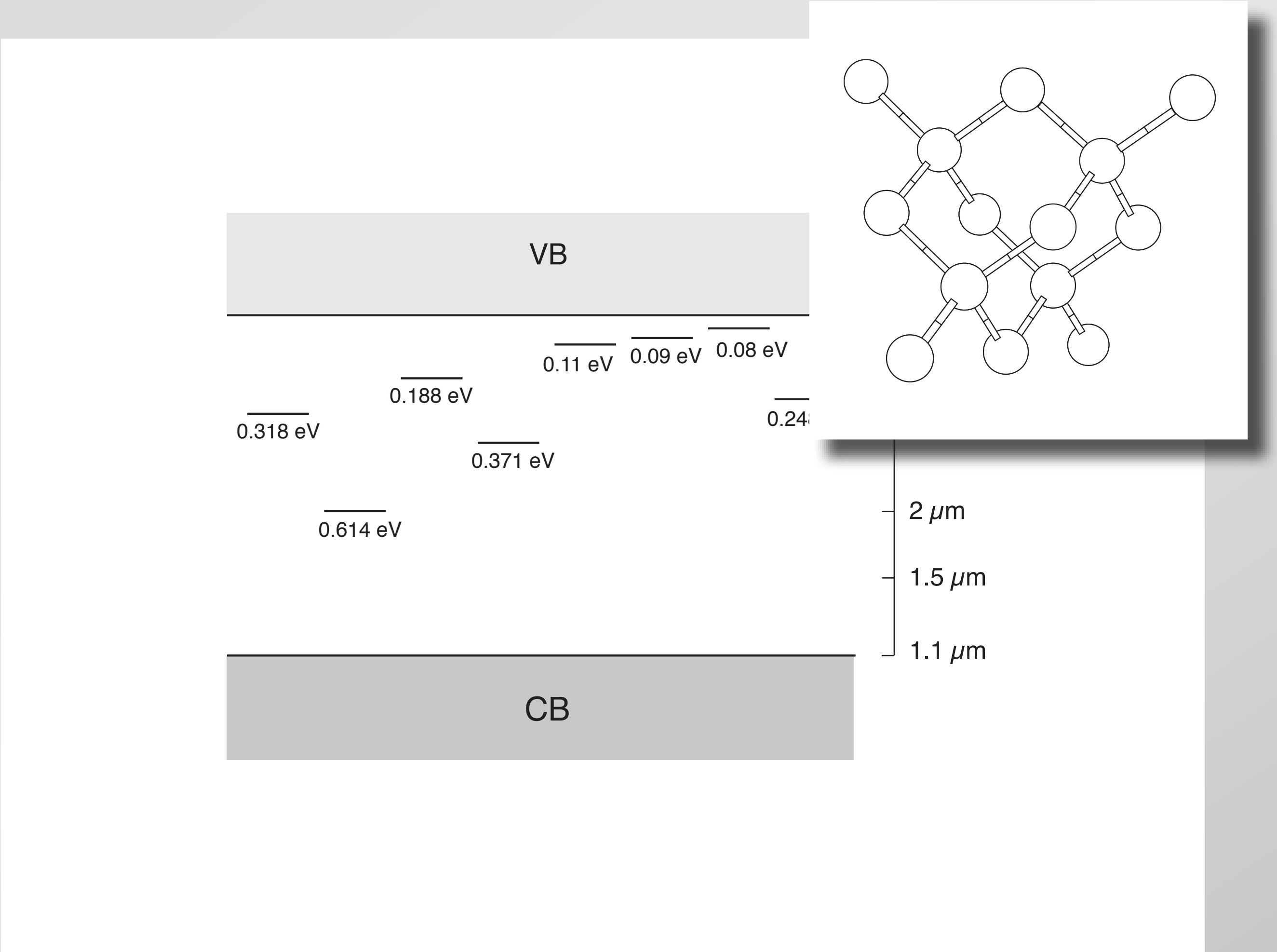

Janzén *et al.*, Phys. Rev. B 29, 1907 (1984)

Optoelectronic properties

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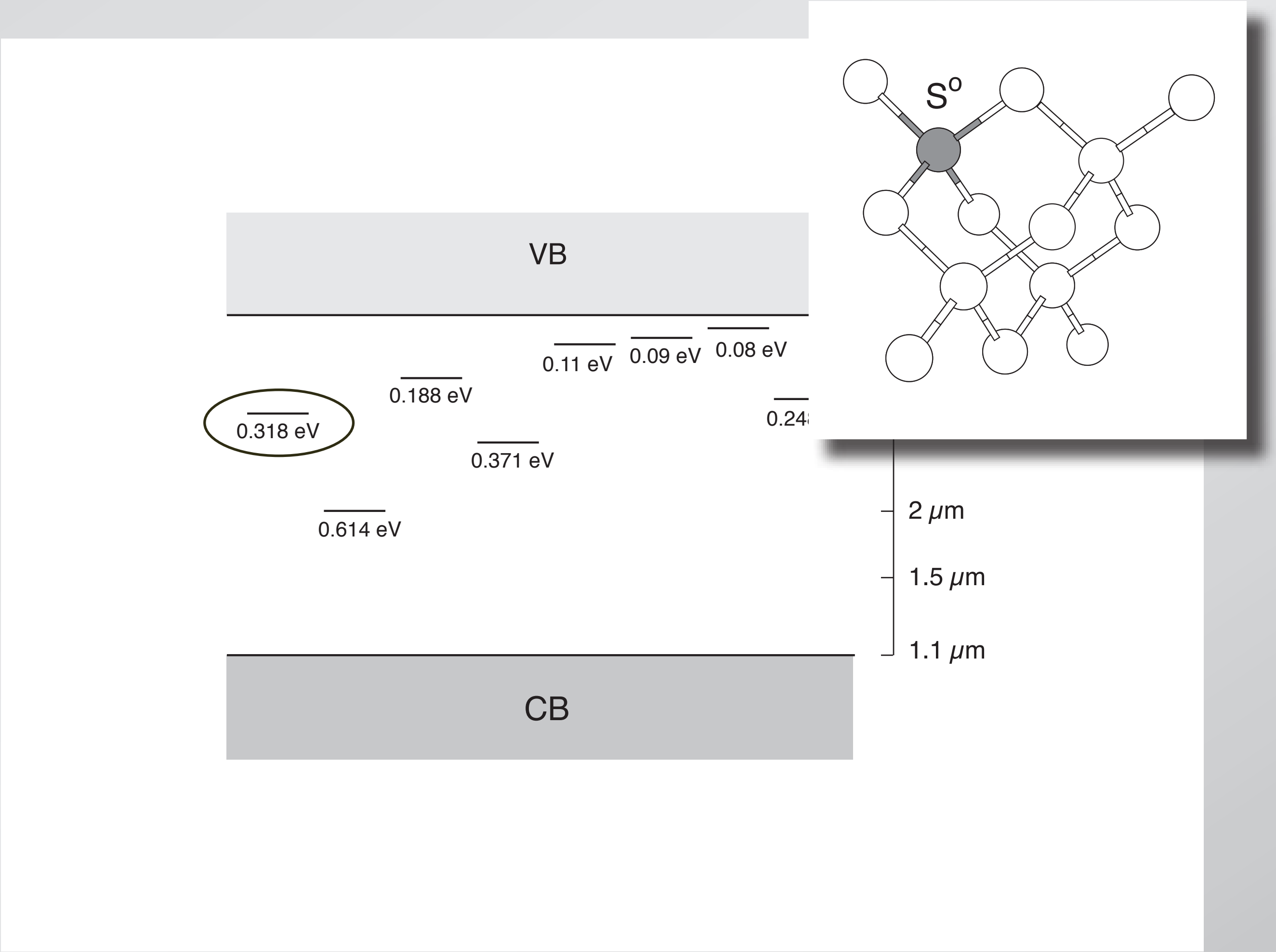

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Optoelectronic properties

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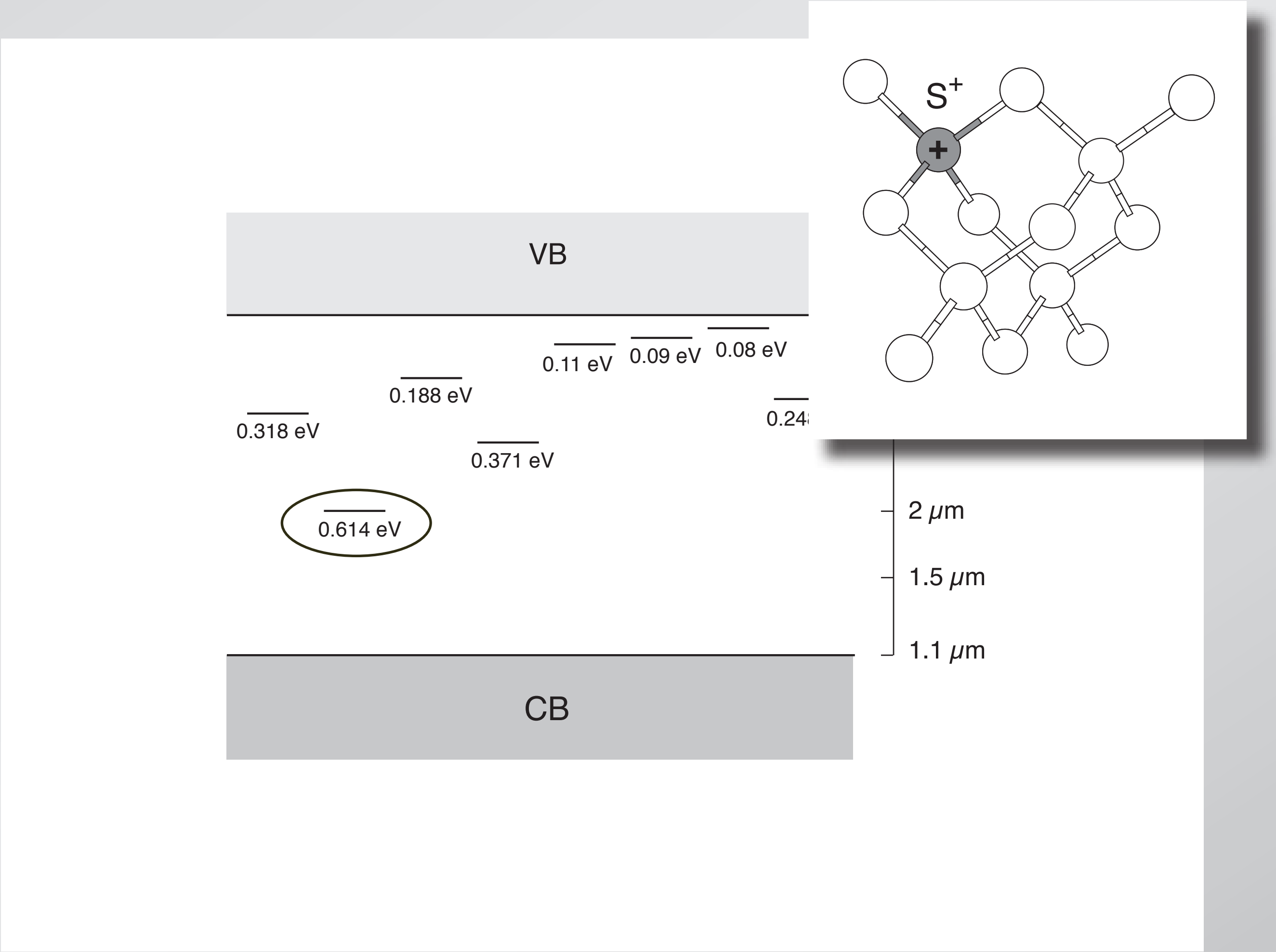

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Optoelectronic properties

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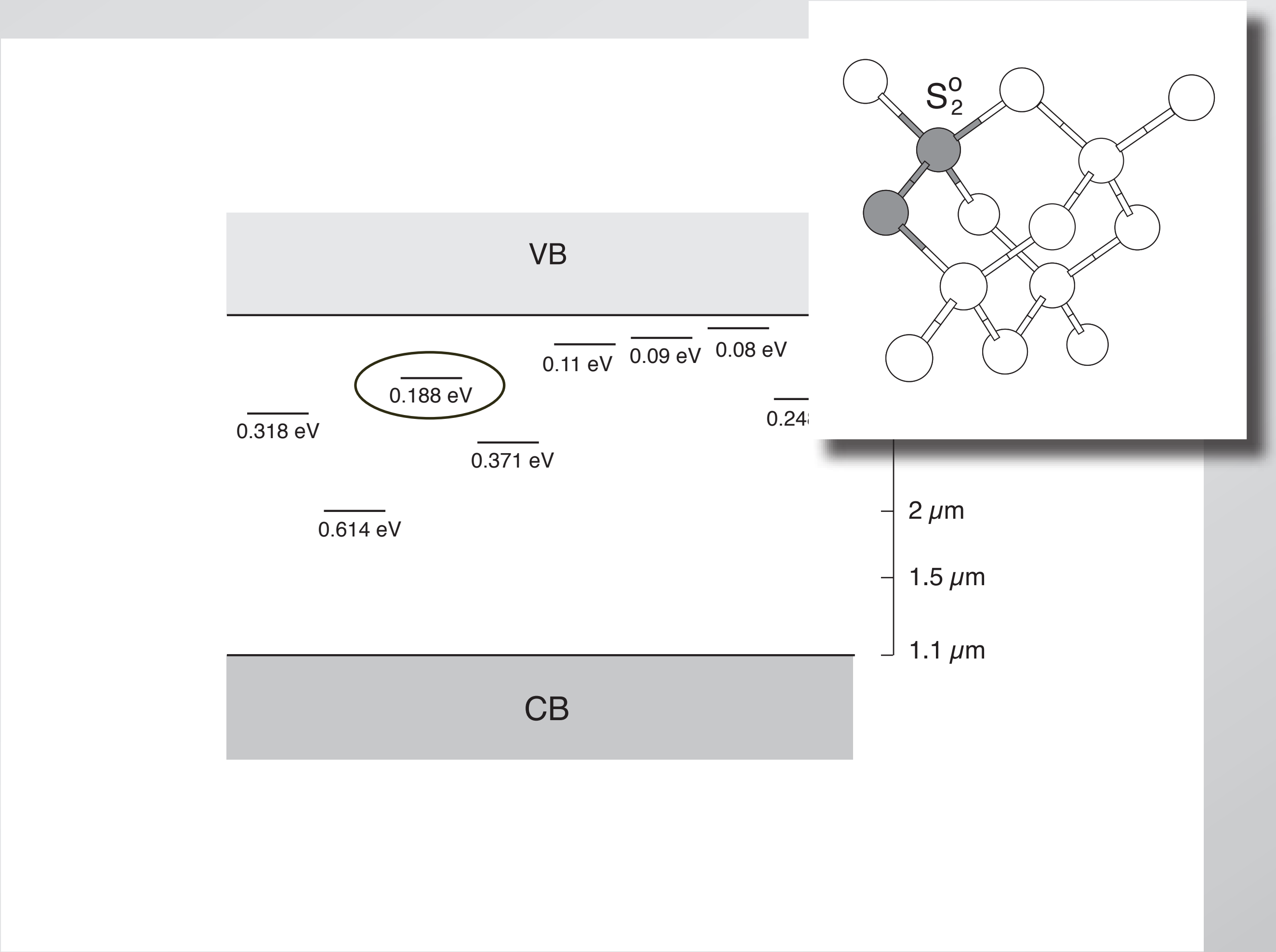

Janzén *et al.*, Phys. Rev. B 29, 1907 (1984)

Optoelectronic properties

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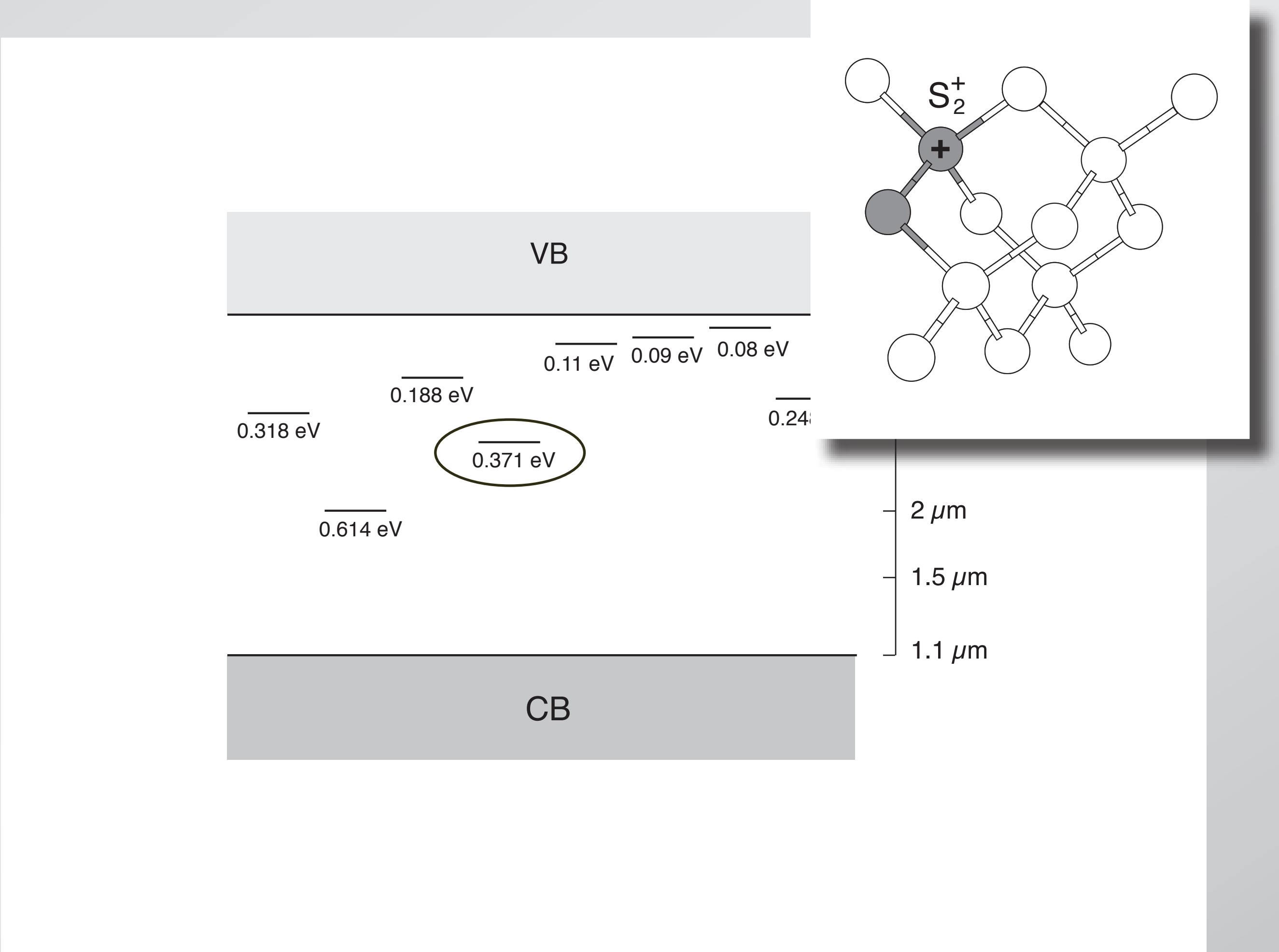

Janzén *et al.*, Phys. Rev. B 29, 1907 (1984)

Optoelectronic properties

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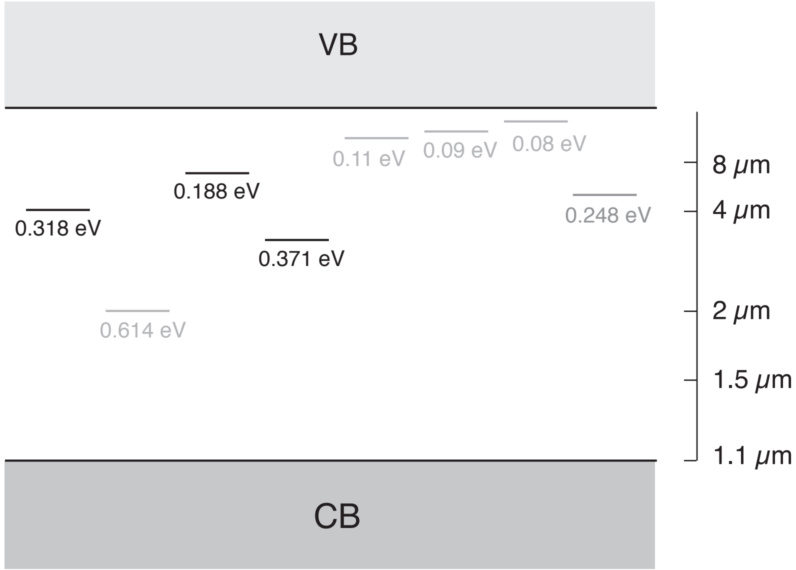
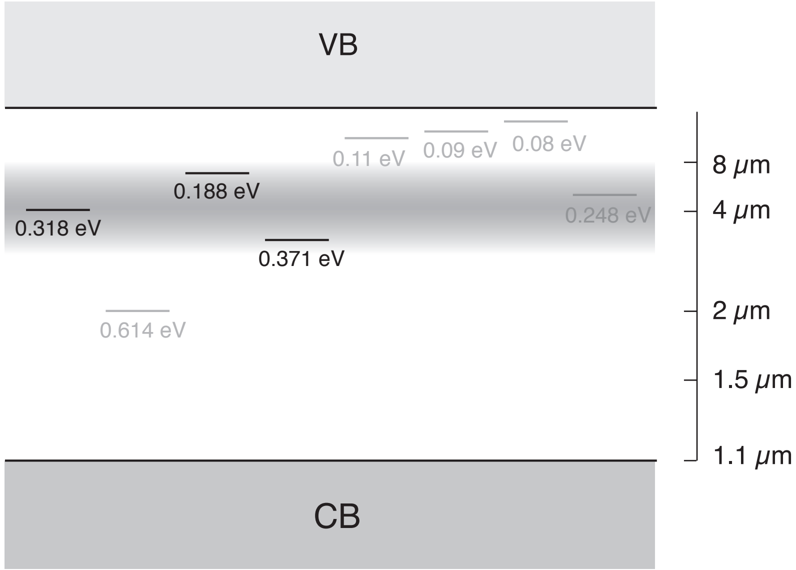


Janzén *et al.*, Phys. Rev. B 29, 1907 (1984)

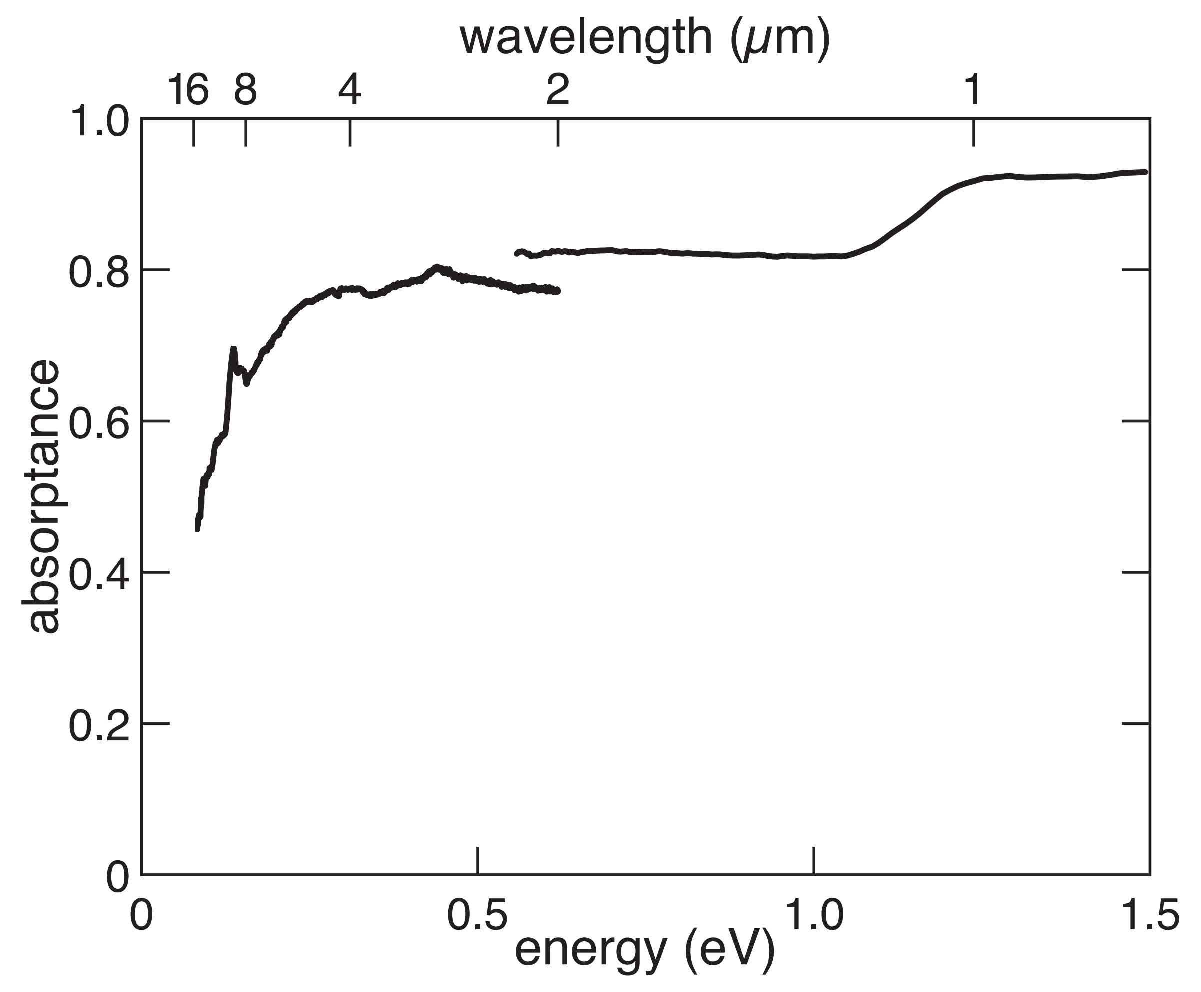
Optoelectronic properties

at high concentration states broaden into band



Optoelectronic properties

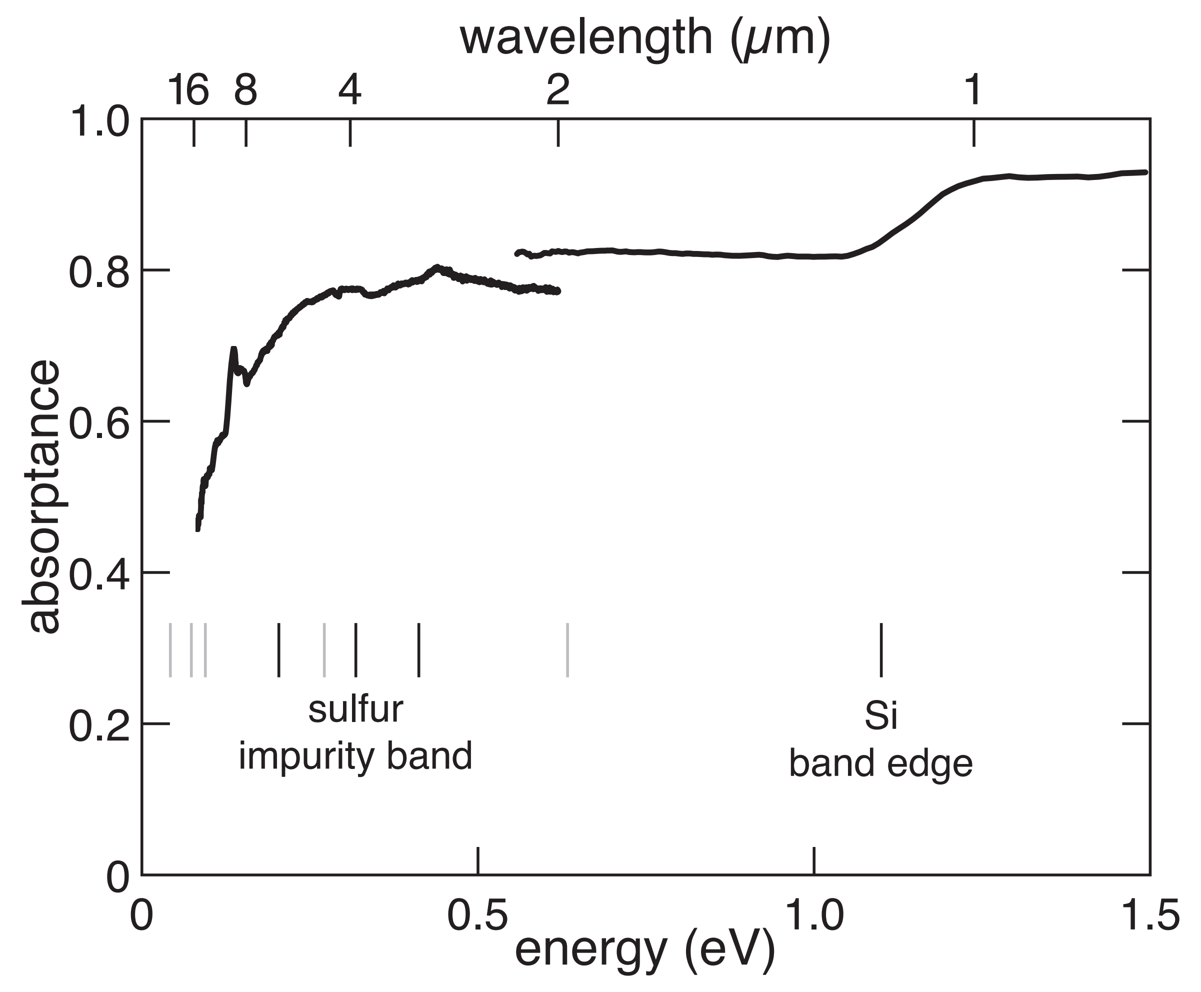
absorptance ($1 - R_{int} - T_{int}$)



Asenbaum, Vienna

Optoelectronic properties

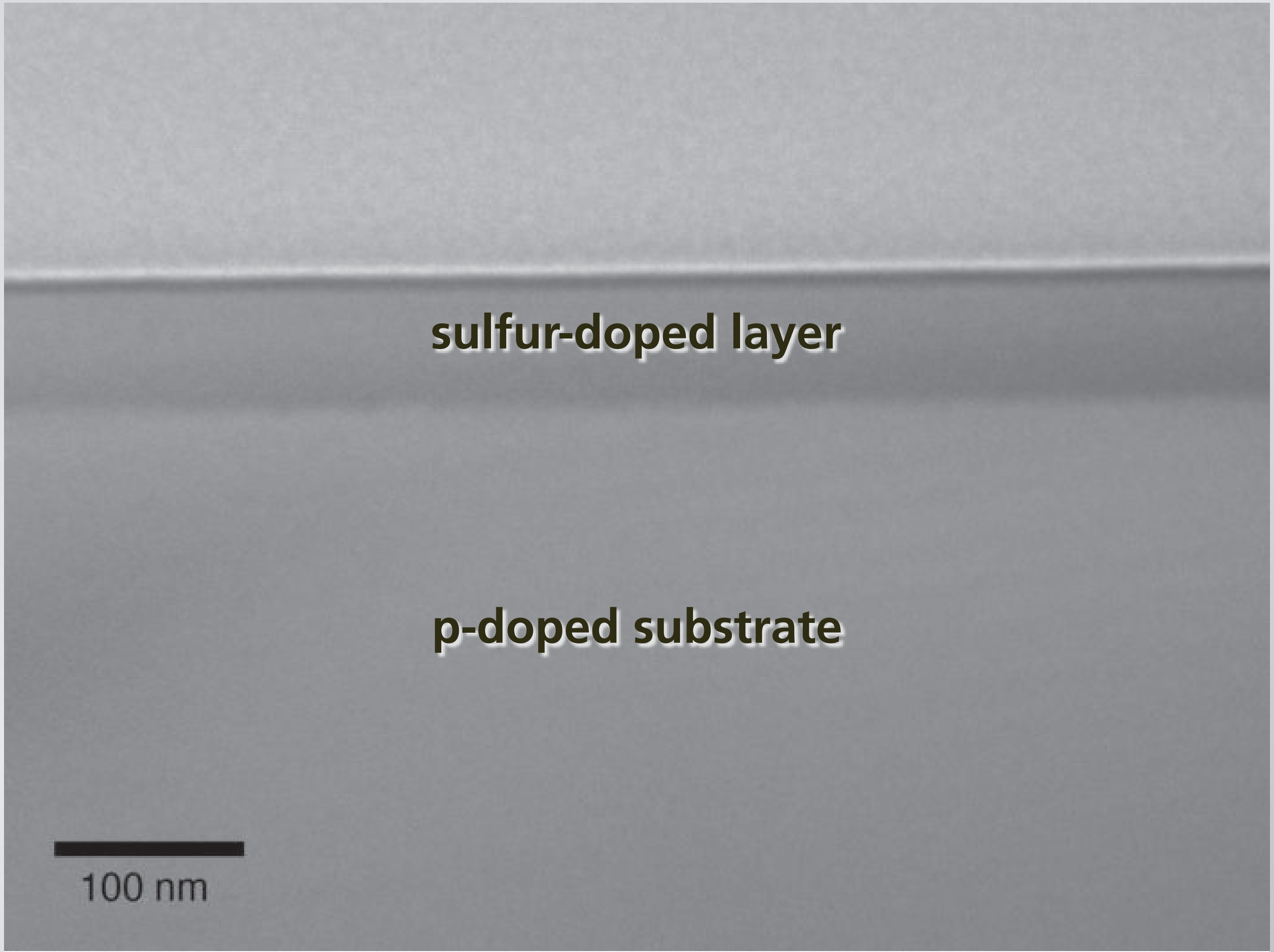
absorptance ($1 - R_{int} - T_{int}$)



Asenbaum, Vienna

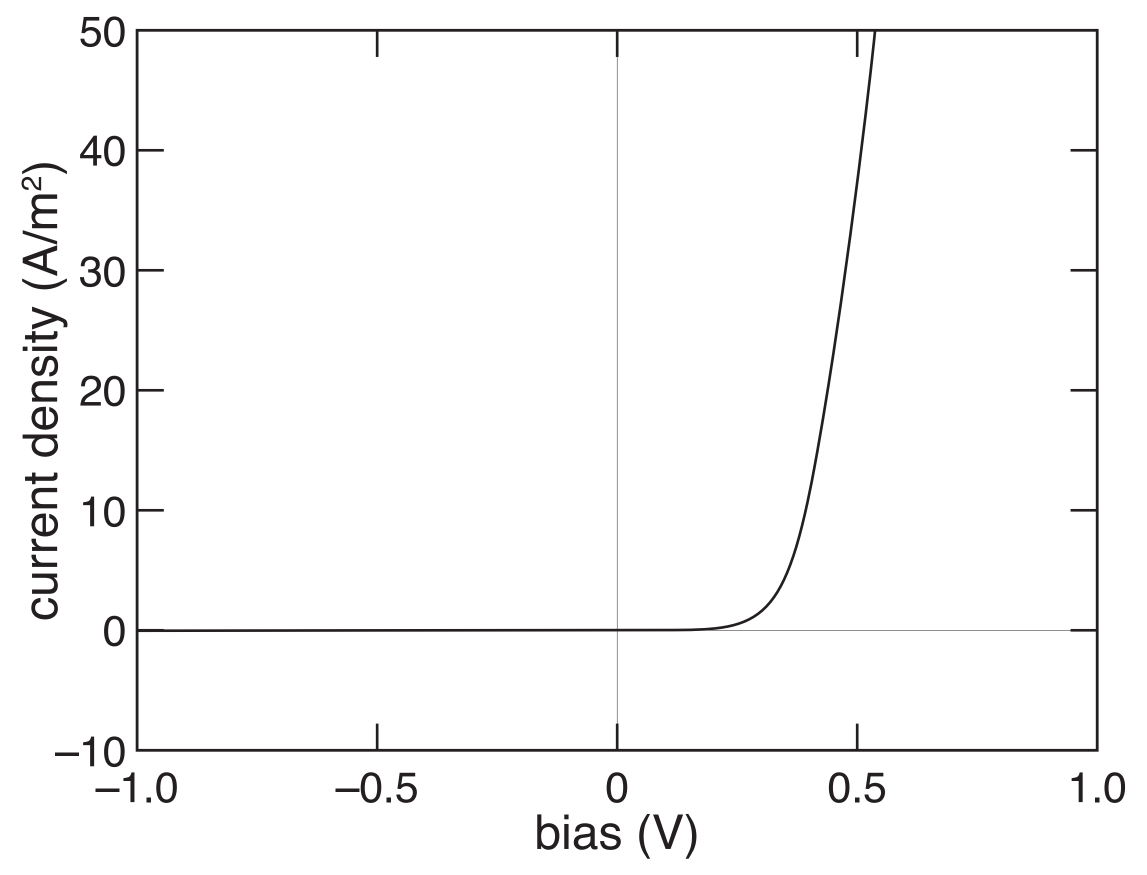
Optoelectronic properties

should have shallow junction below surface



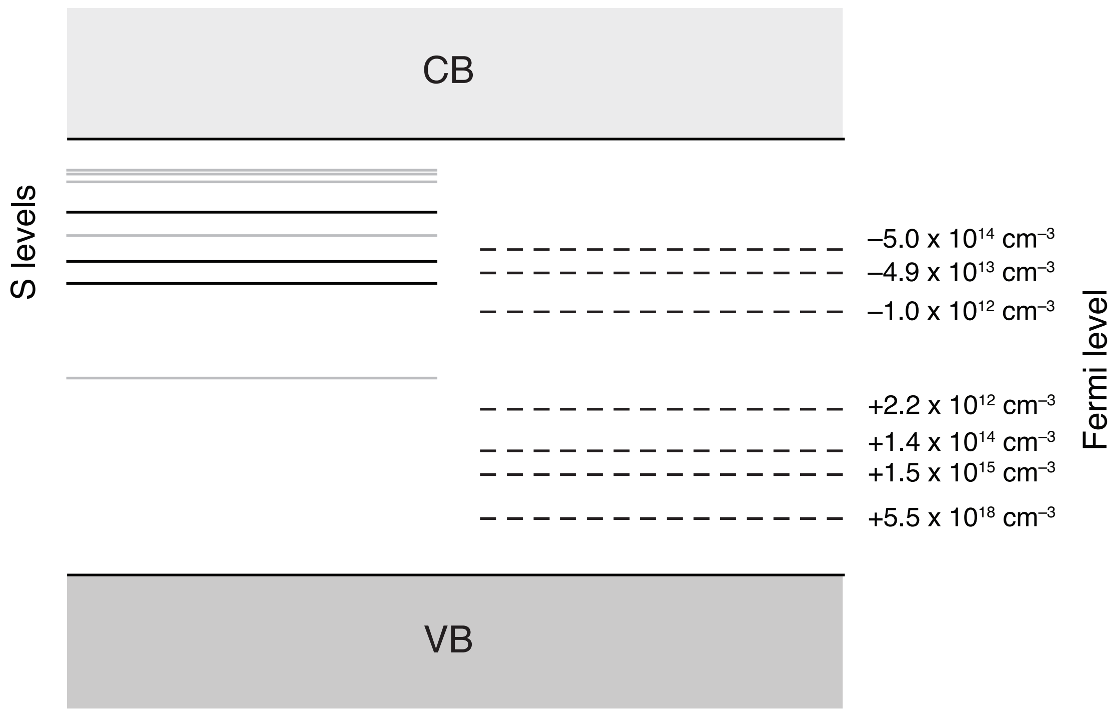
Optoelectronic properties

excellent rectification (after annealing)



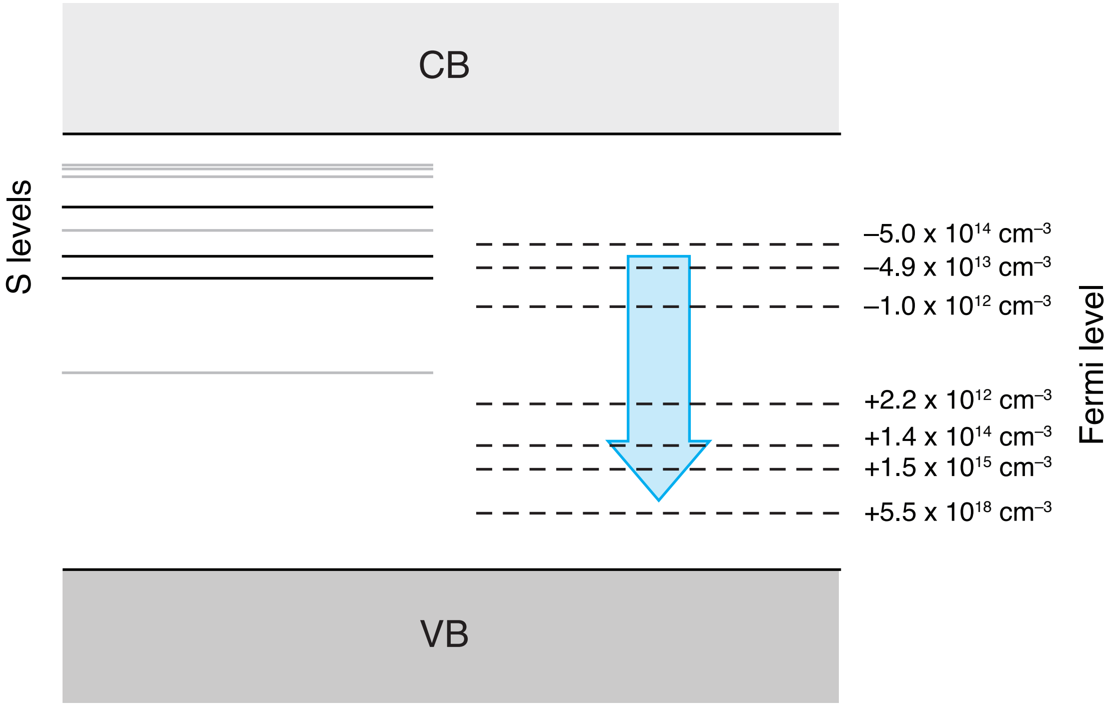
Optoelectronic properties

probe impurity states by varying Fermi level in substrate



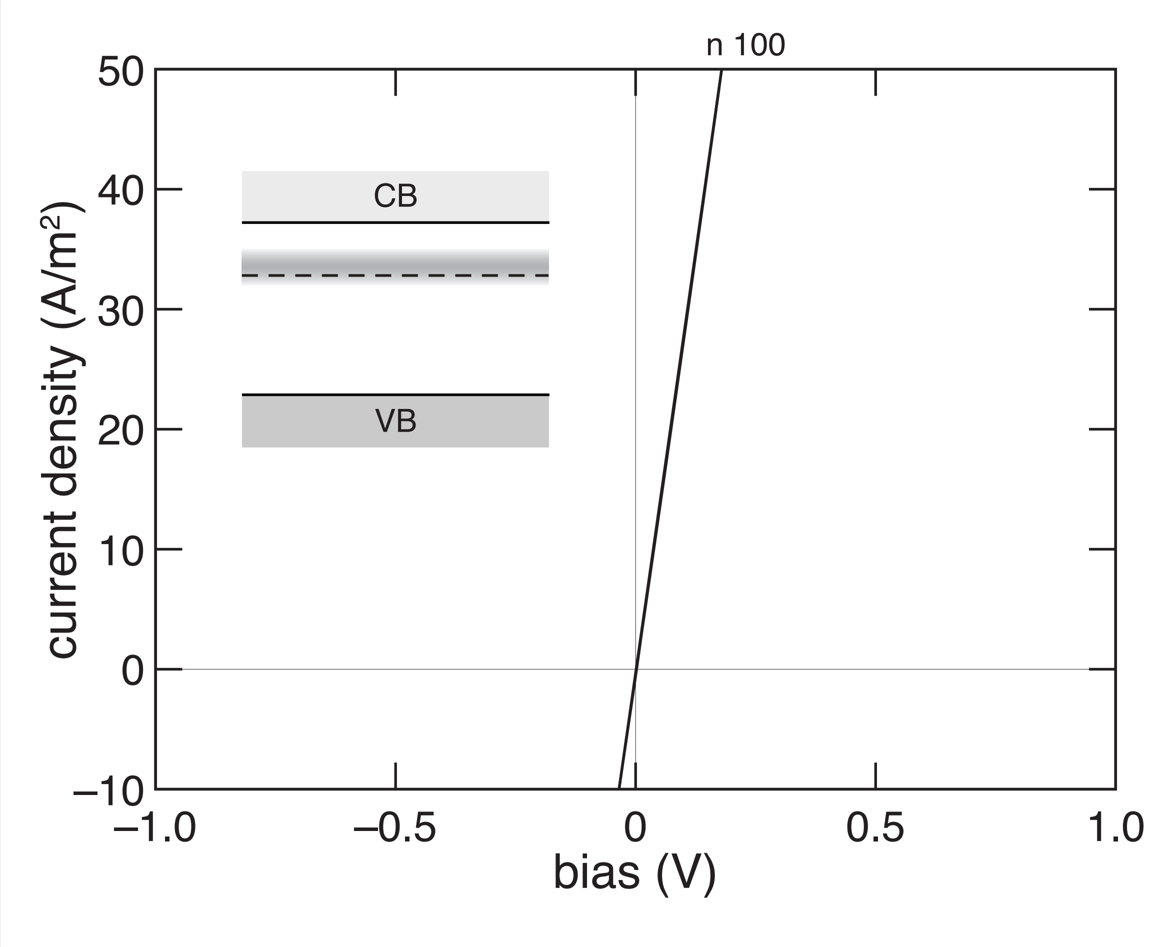
Optoelectronic properties

probe impurity states by varying Fermi level in substrate



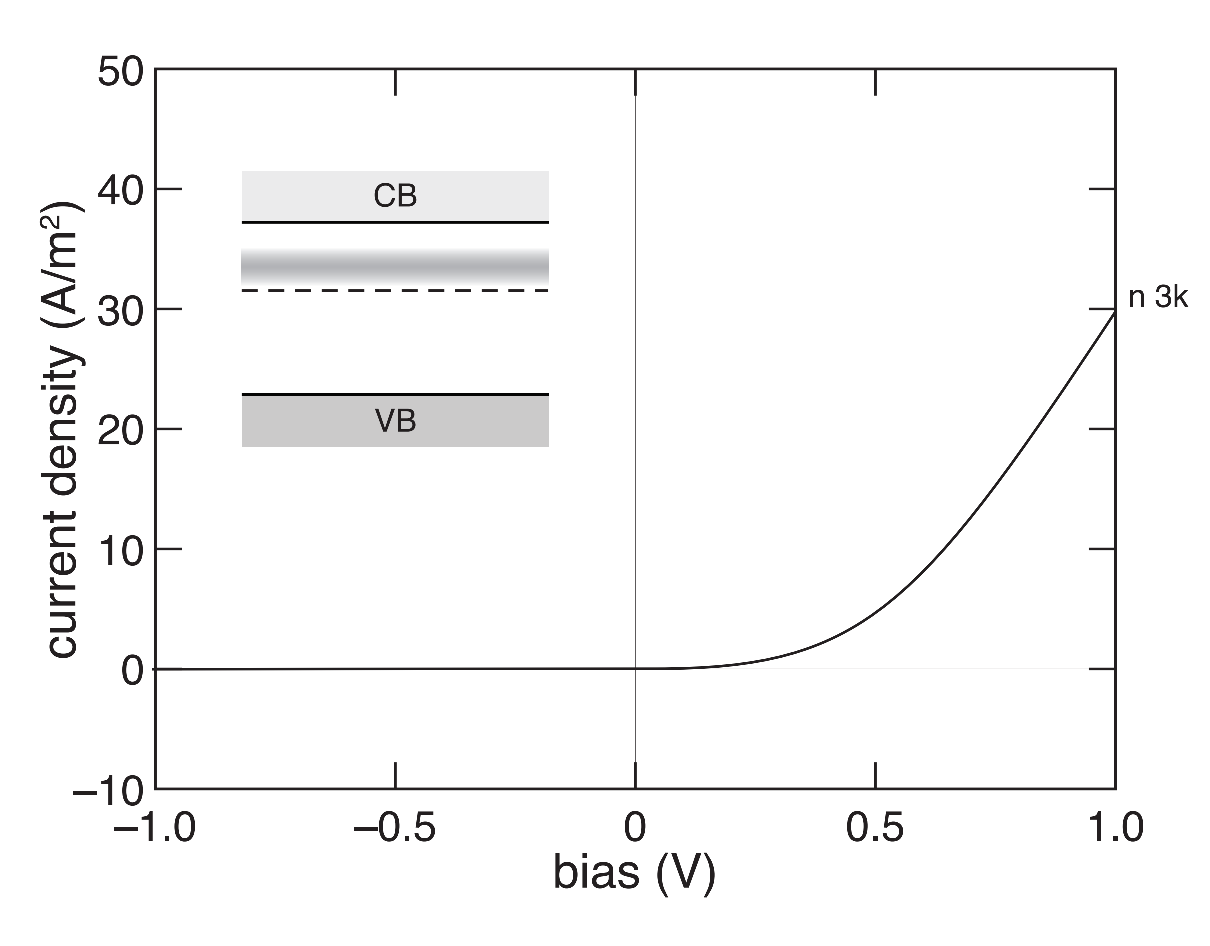
Optoelectronic properties

vary substrate doping type and resistivity



Optoelectronic properties

vary substrate doping type and resistivity



Optoelectronic properties

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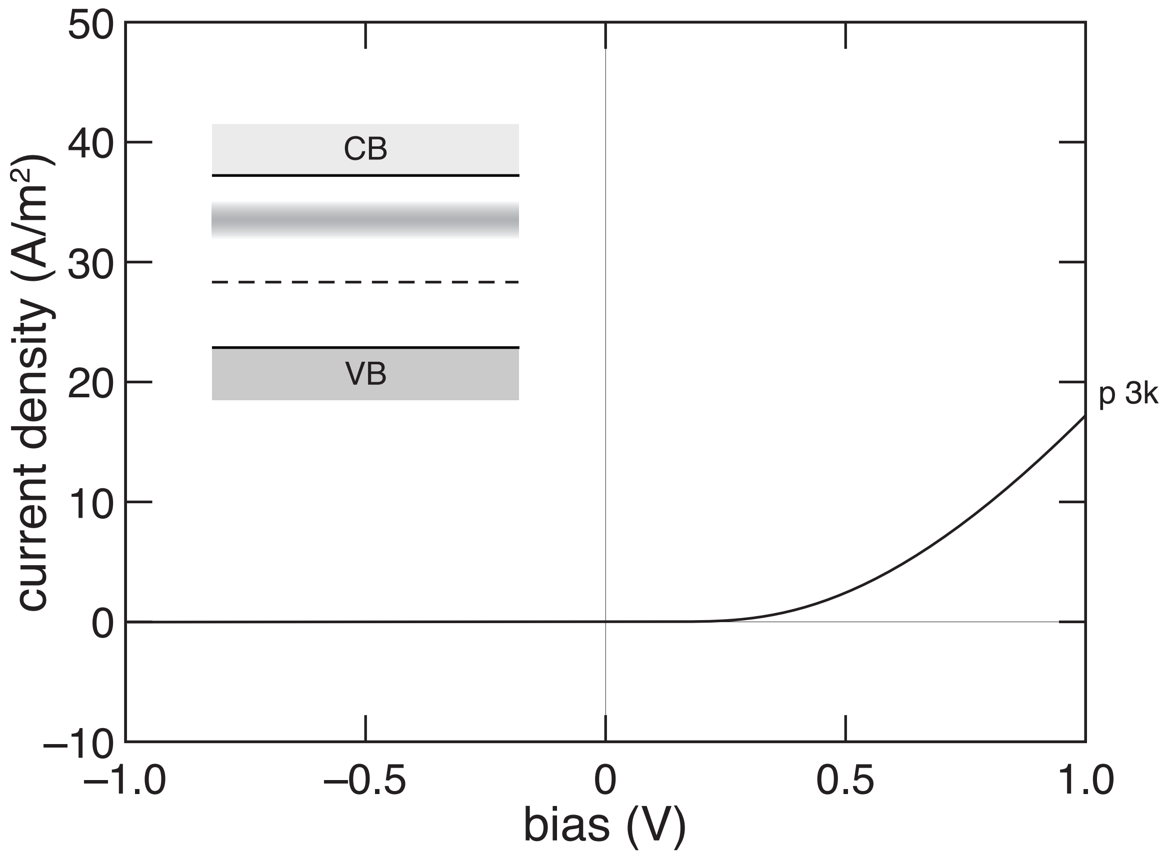
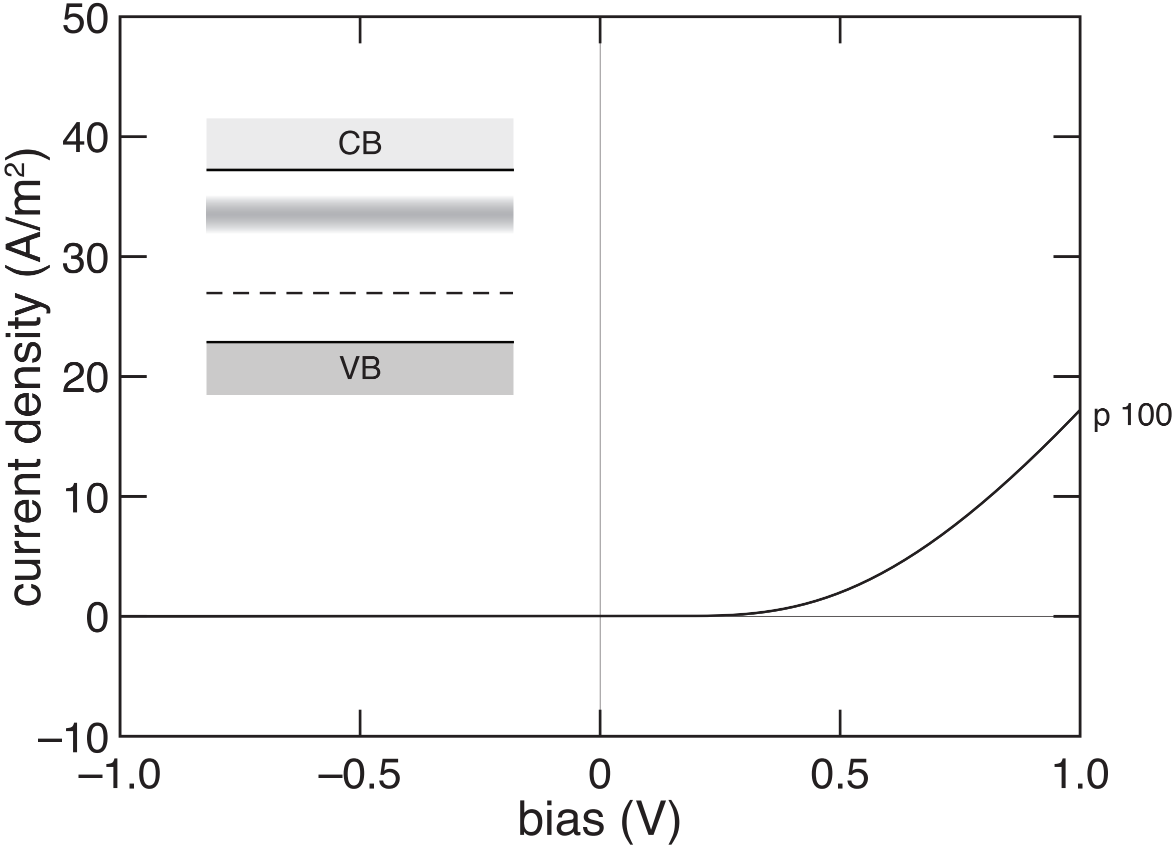


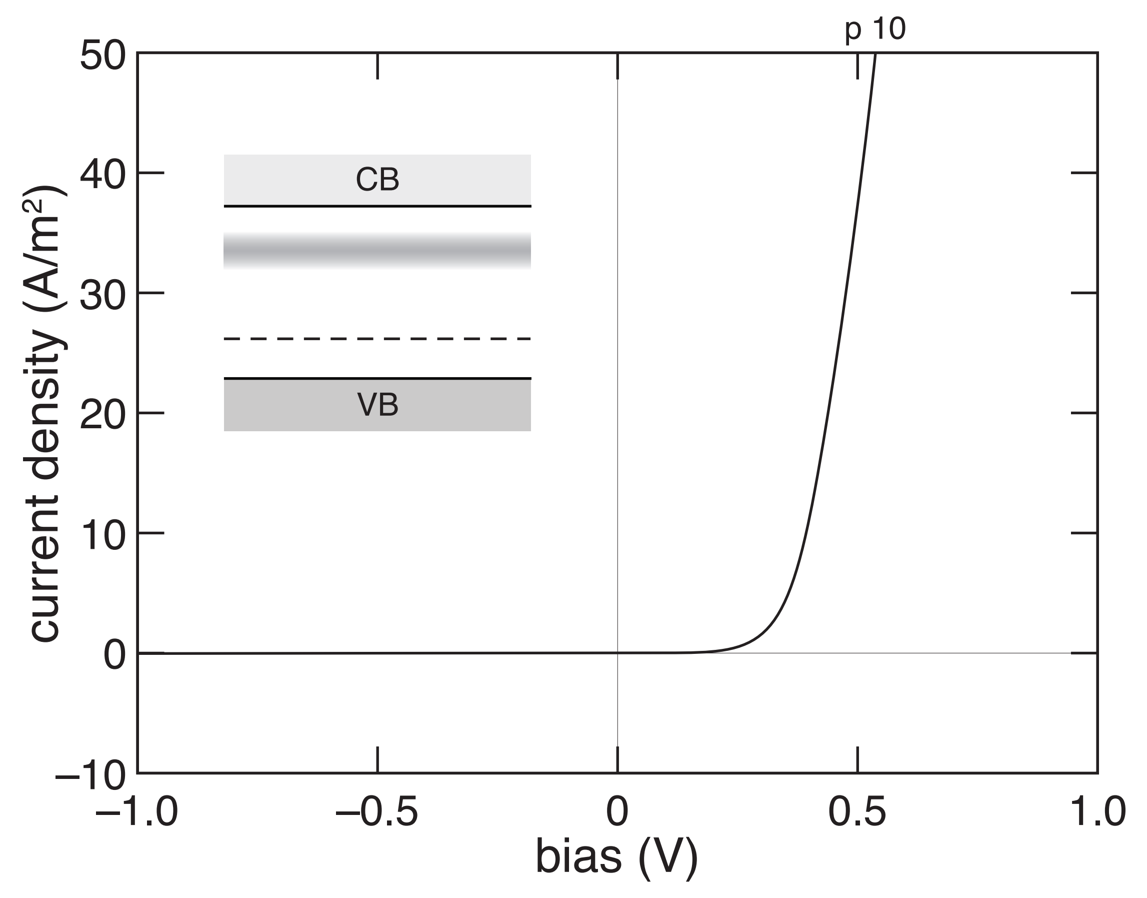
Optoelectronic properties

vary substrate doping type and resistivity



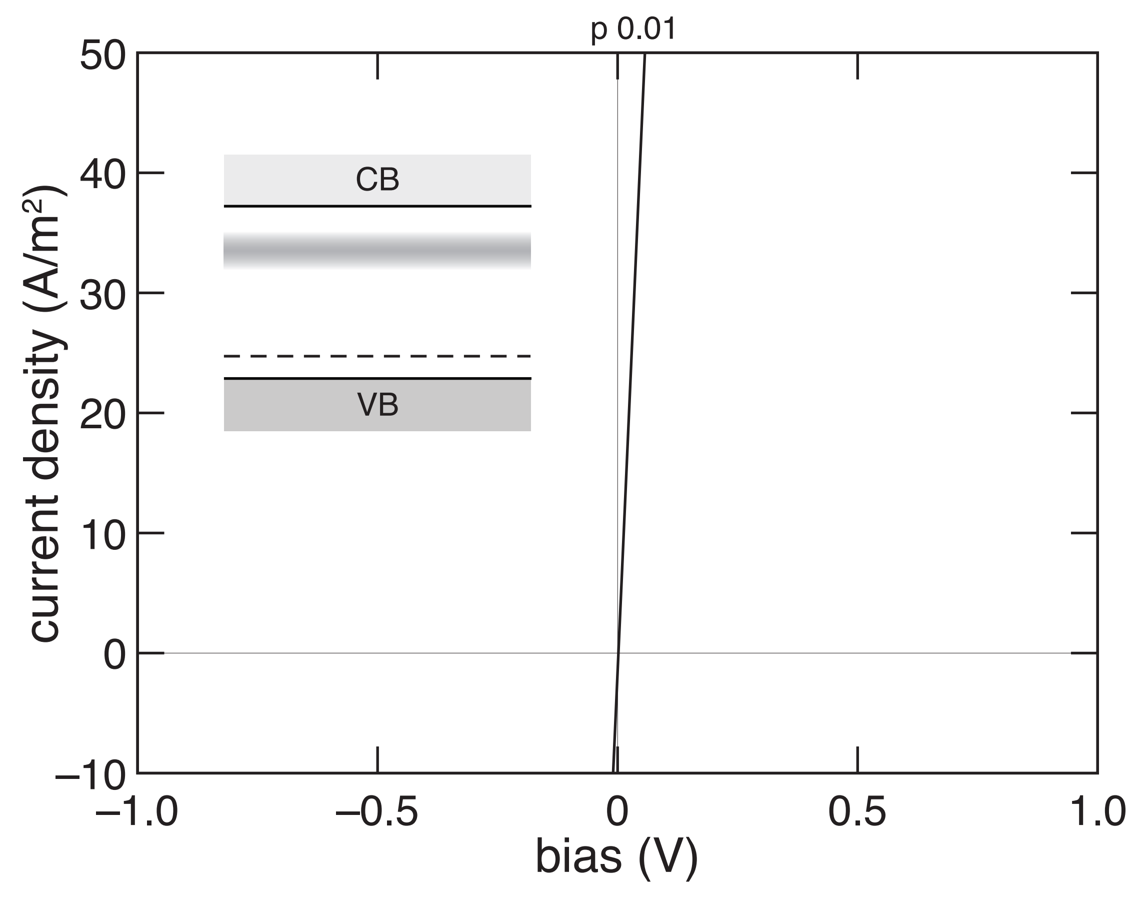
Optoelectronic properties

vary substrate doping type and resistivity



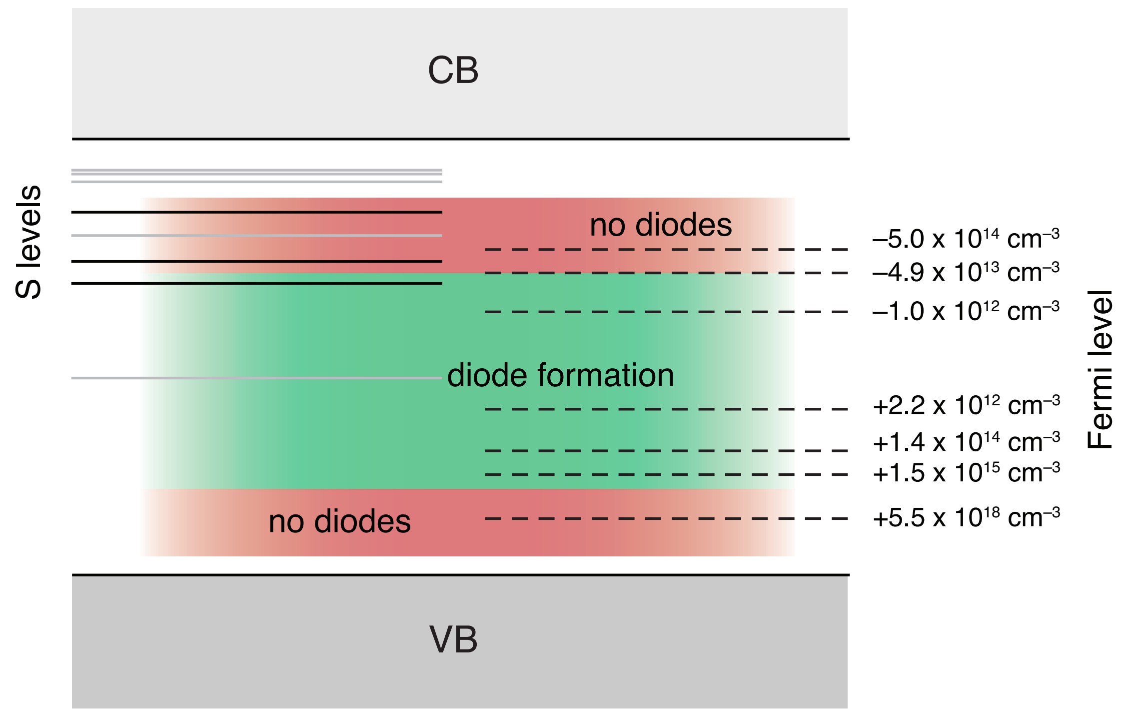
Optoelectronic properties

vary substrate doping type and resistivity



Optoelectronic properties

probe impurity states by varying Fermi level in substrate



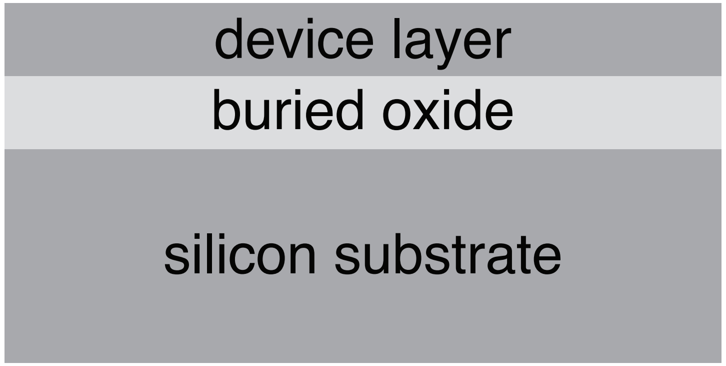
Optoelectronic properties

IV behavior consistent with

impurity band between 200 and 400 meV

Optoelectronic properties

isolate surface layer for Hall measurements



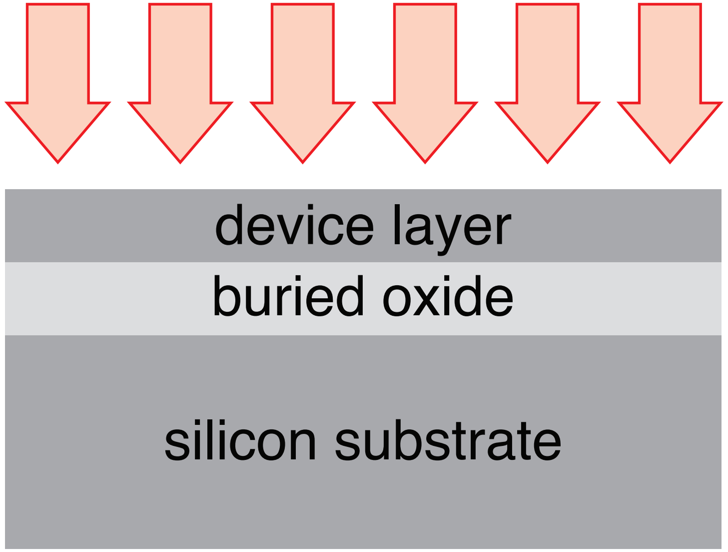
device layer

buried oxide

silicon substrate

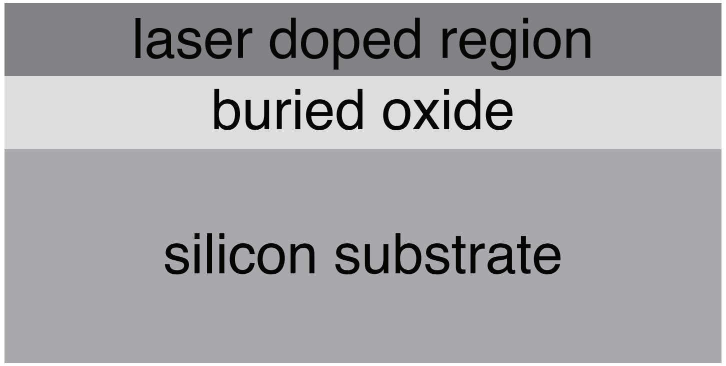
Optoelectronic properties

isolate surface layer for Hall measurements



Optoelectronic properties

isolate surface layer for Hall measurements



Optoelectronic properties

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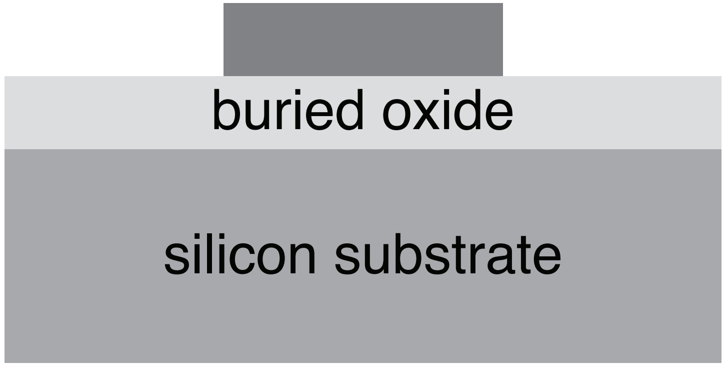
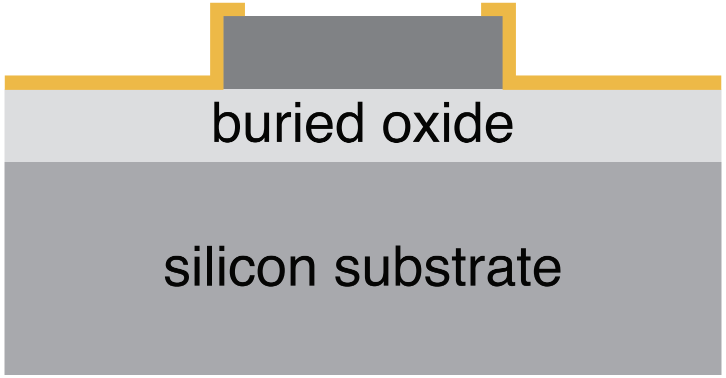
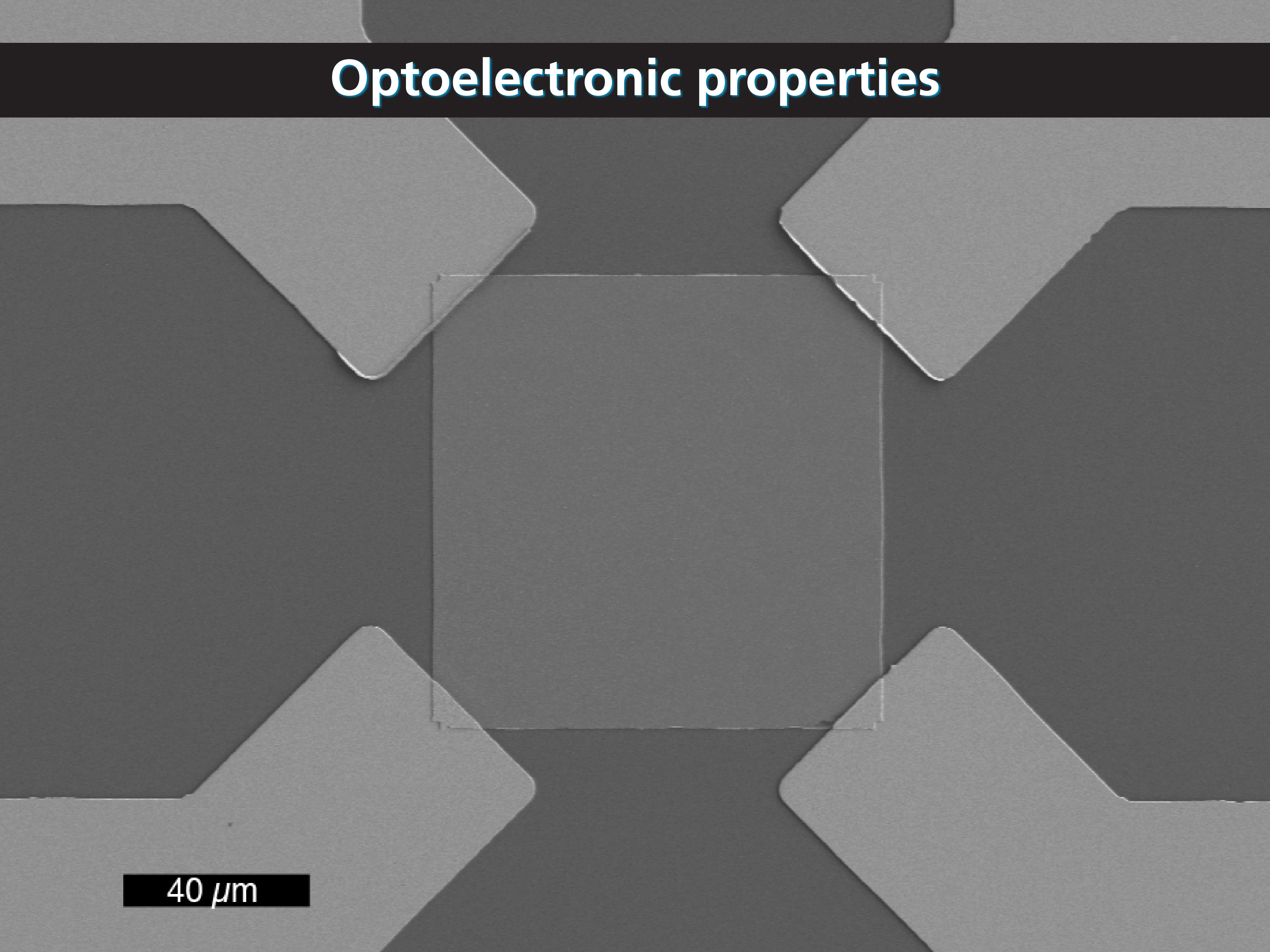


Optoelectronic properties

isolate surface layer for Hall measurements

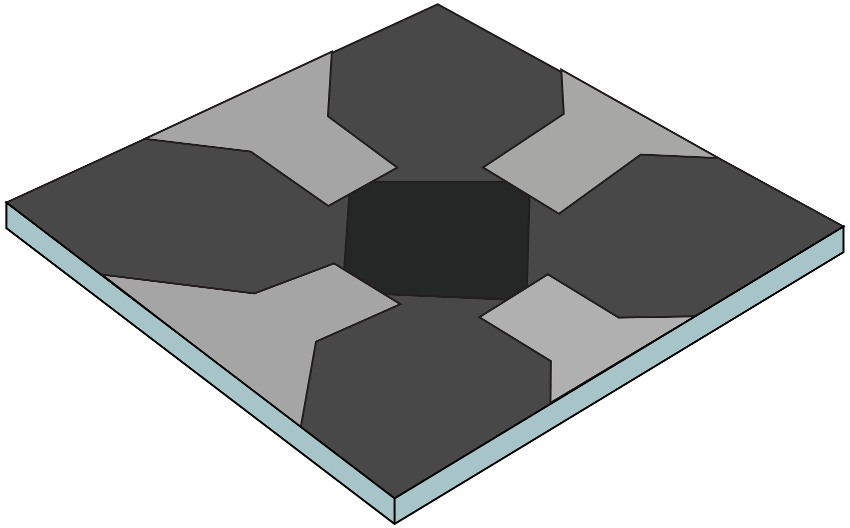


Optoelectronic properties



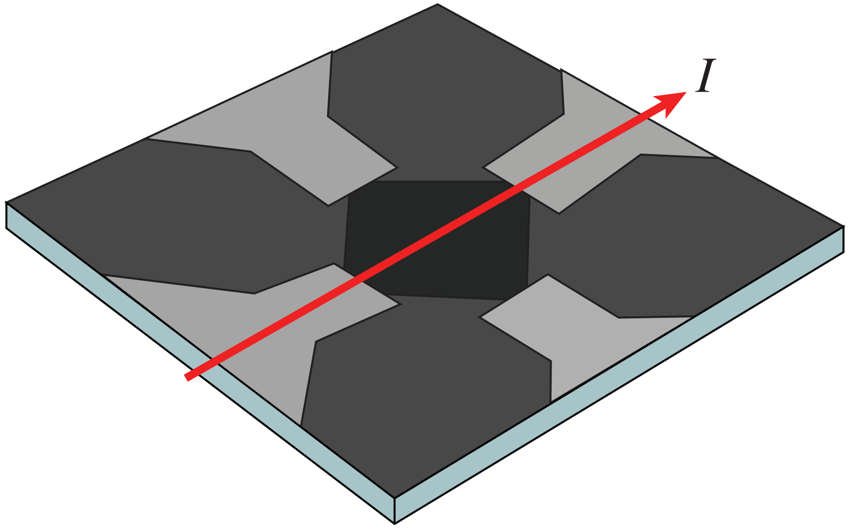
Optoelectronic properties

Hall measurements



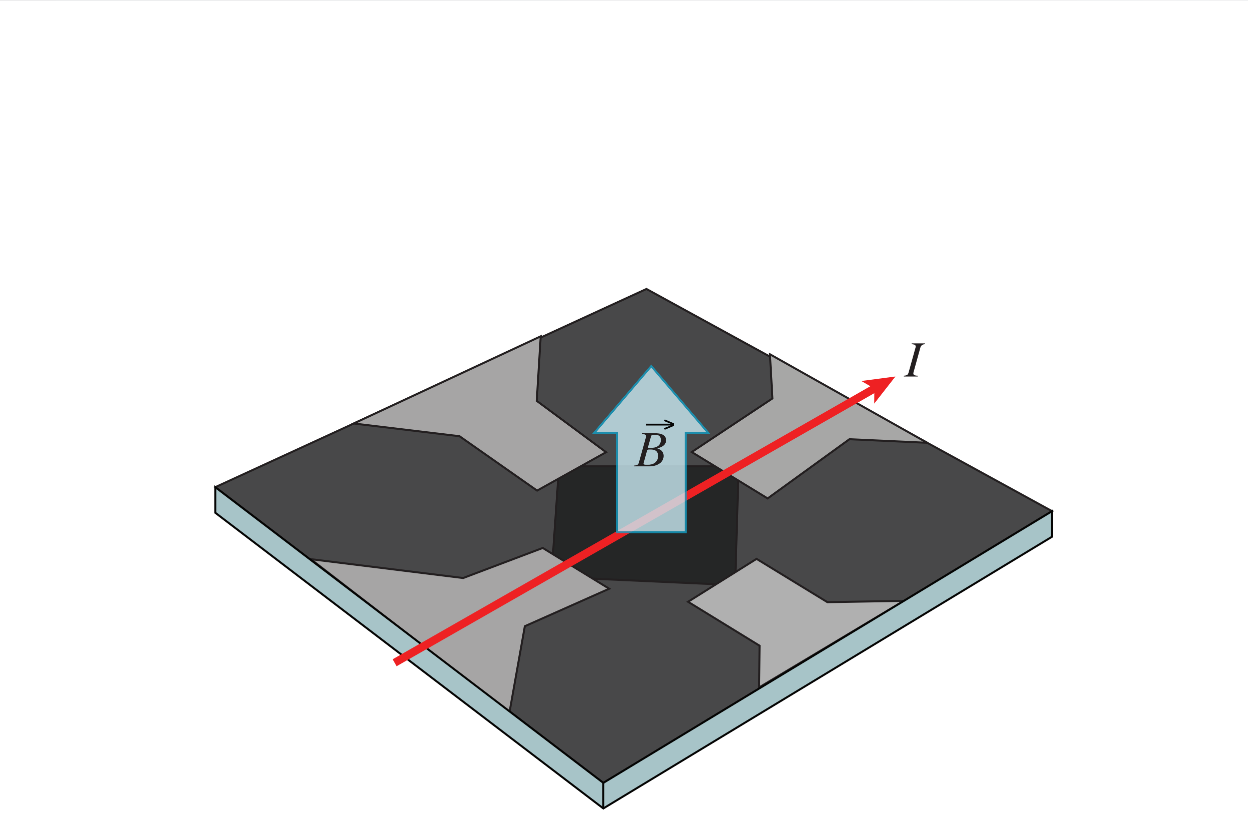
Optoelectronic properties

Hall measurements



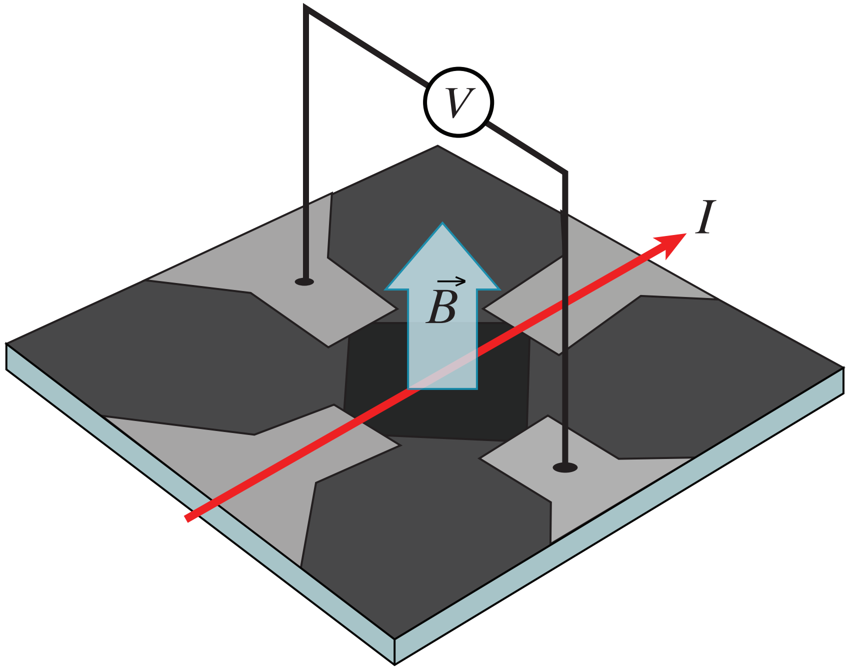
Optoelectronic properties

Hall measurements



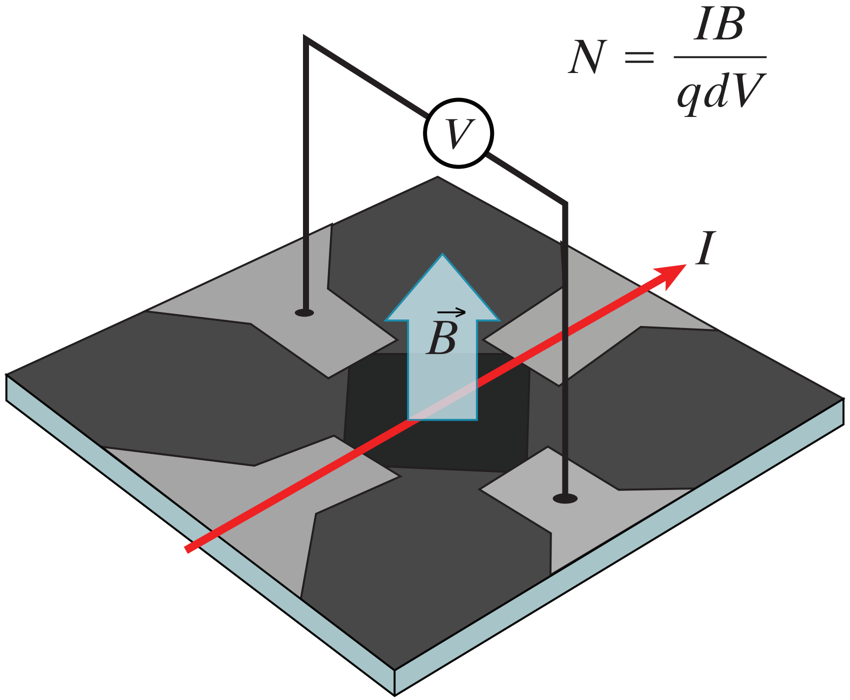
Optoelectronic properties

Hall measurements



Optoelectronic properties

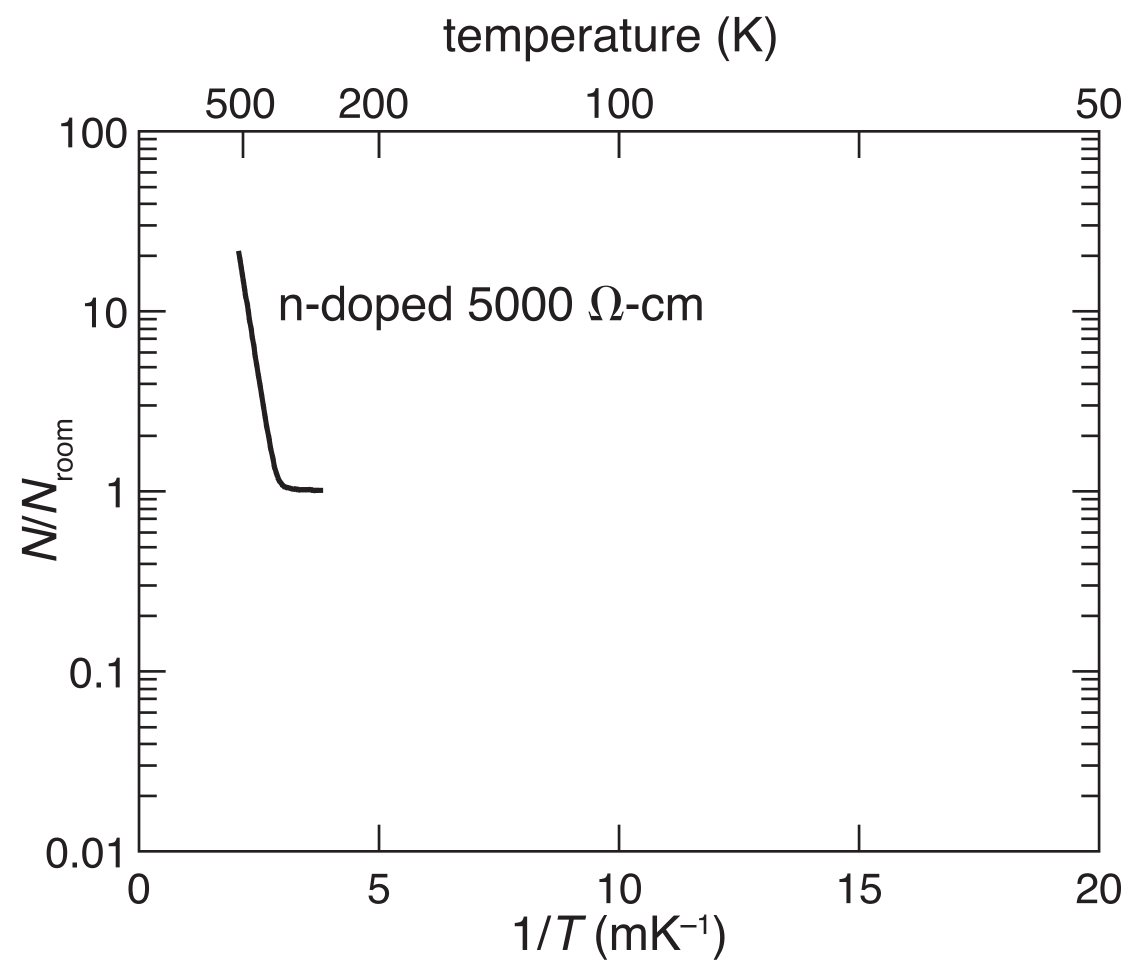
Hall measurements



$$N = \frac{IB}{qdV}$$

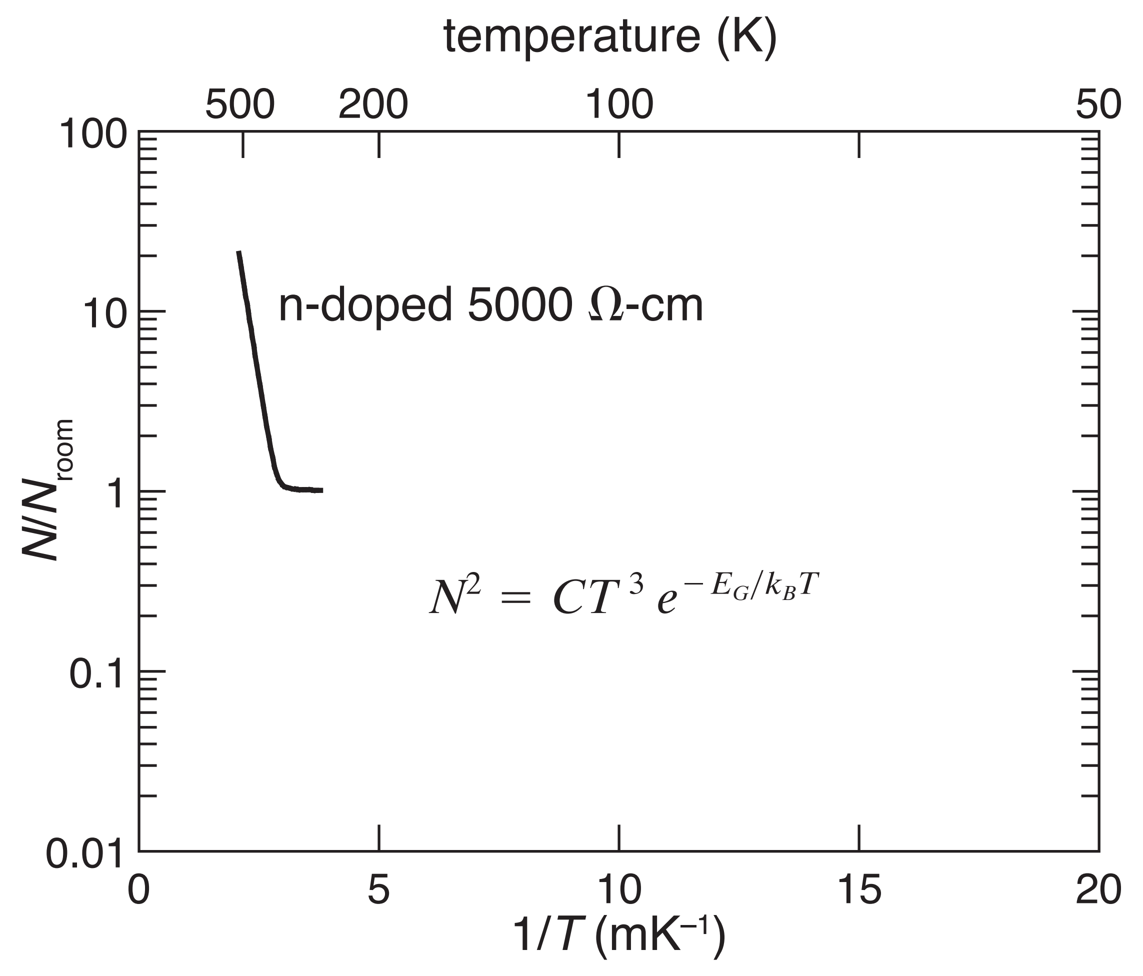
Optoelectronic properties

Hall measurements



Optoelectronic properties

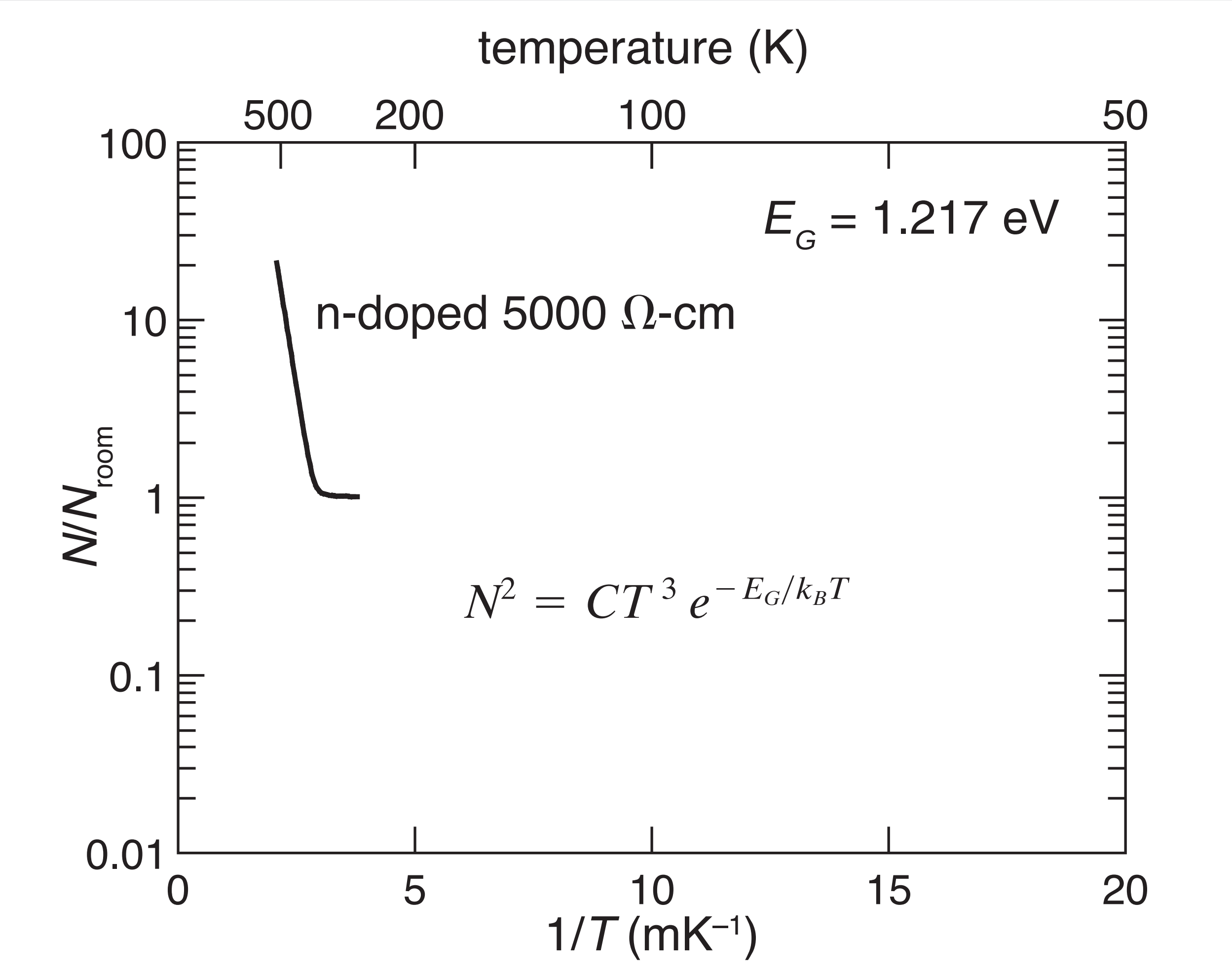
Hall measurements



$$N^2 = CT^3 e^{-E_G/k_BT}$$

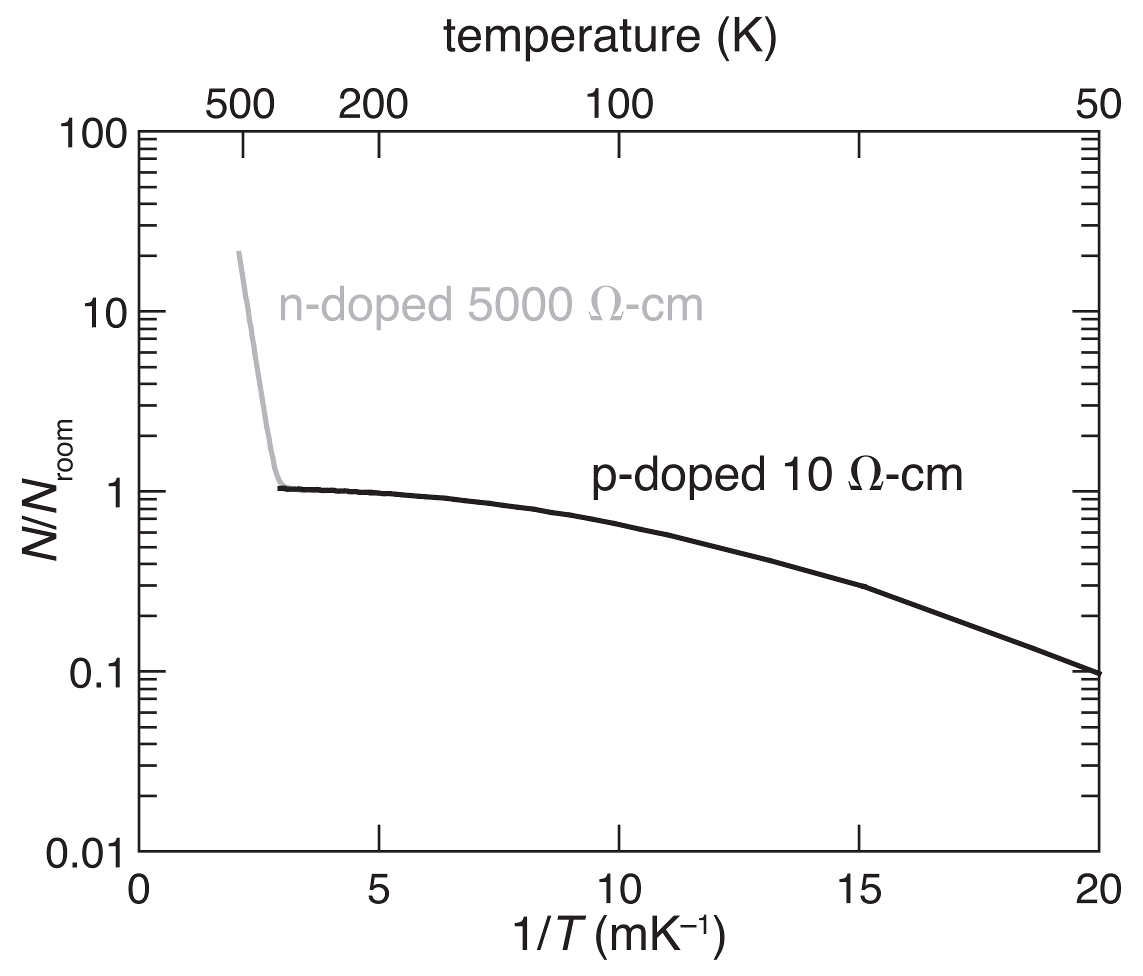
Optoelectronic properties

Hall measurements



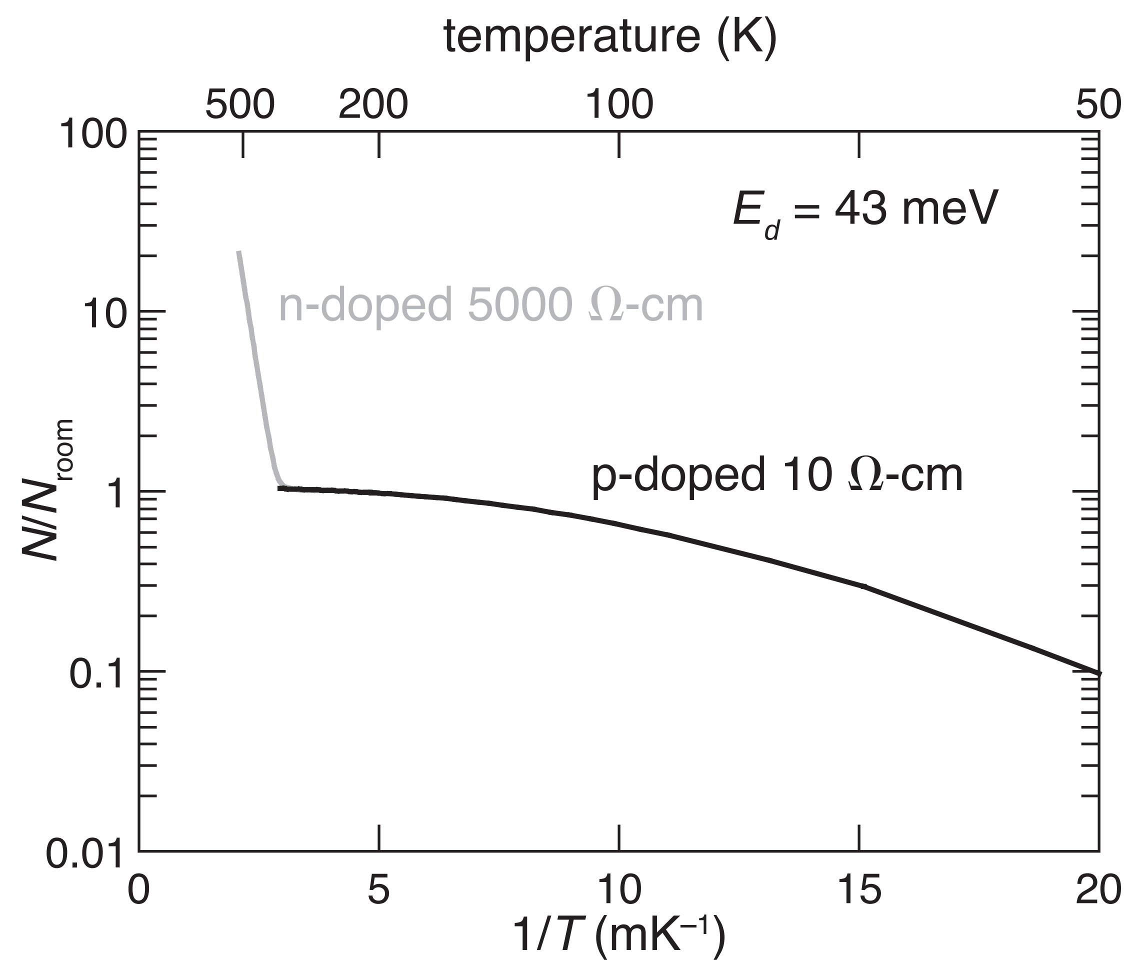
Optoelectronic properties

Hall measurements



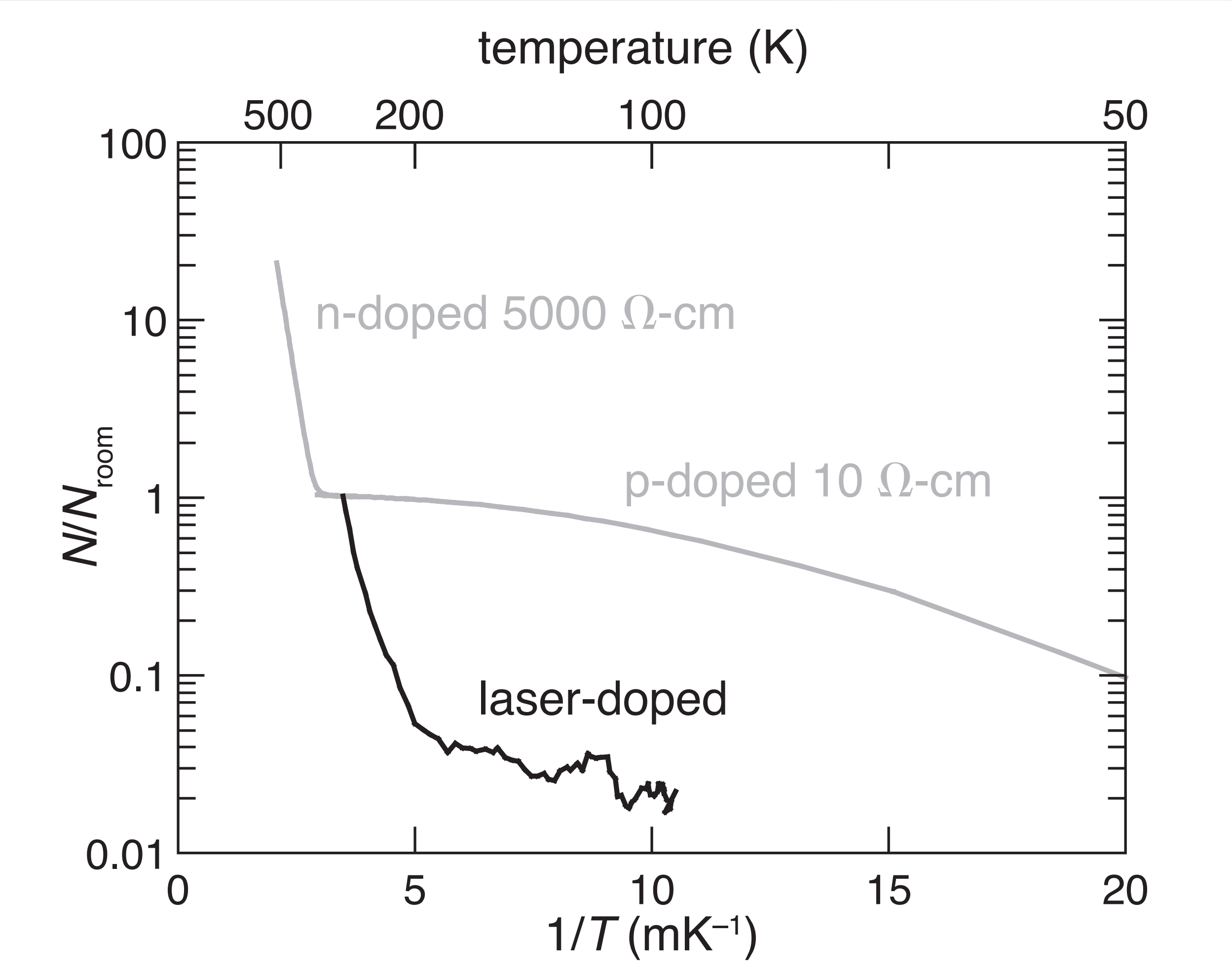
Optoelectronic properties

Hall measurements



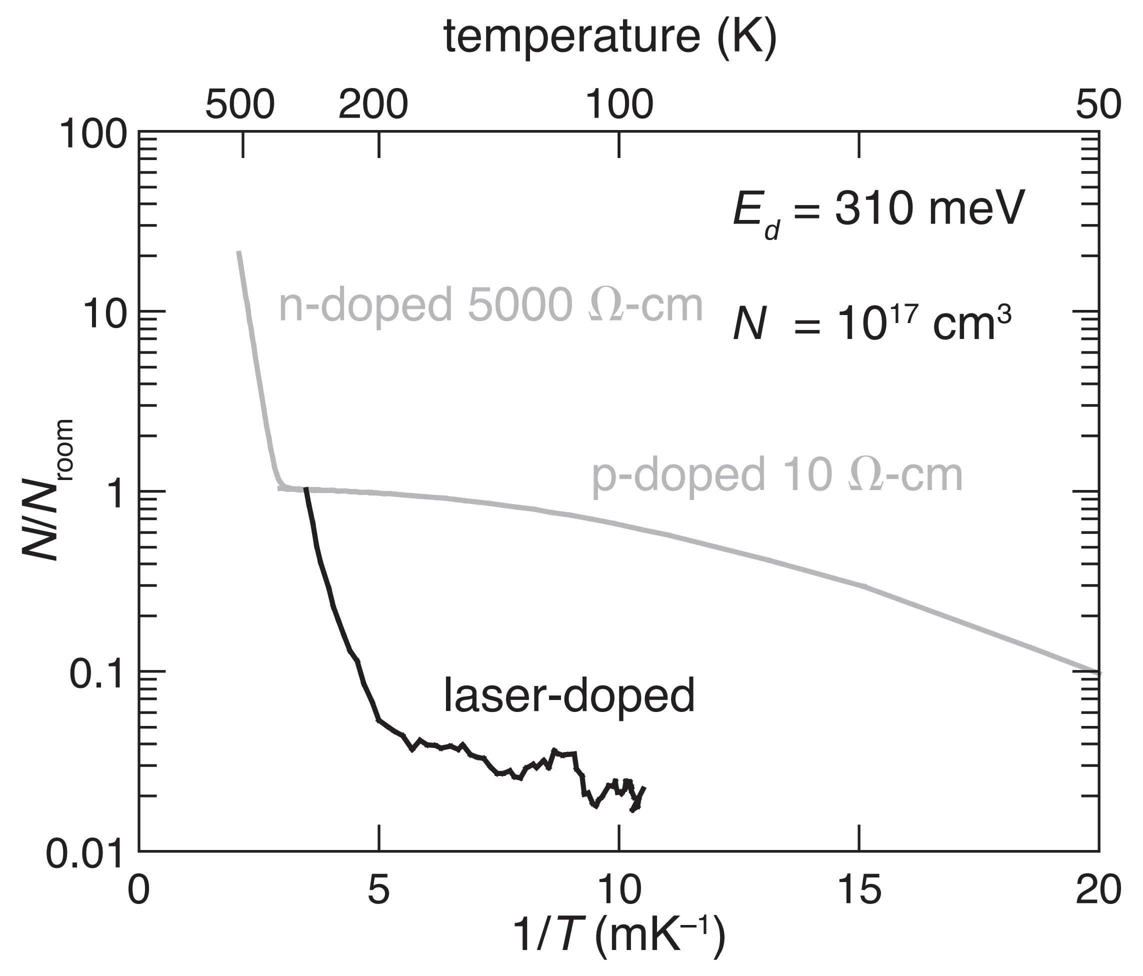
Optoelectronic properties

Hall measurements



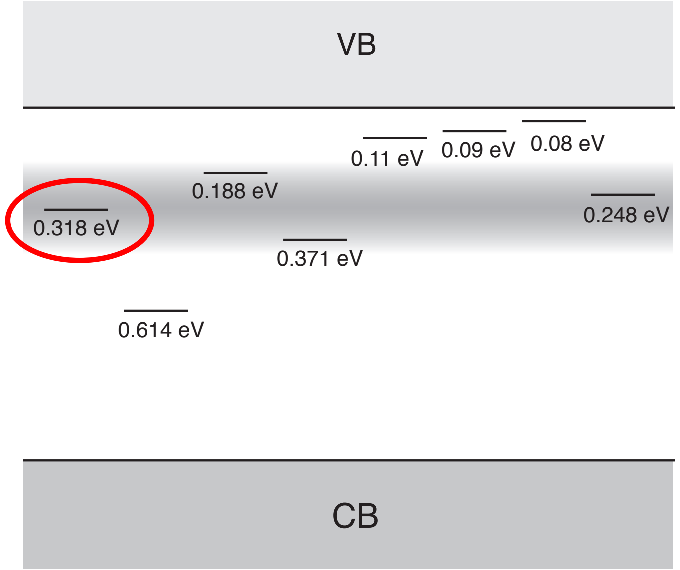
Optoelectronic properties

Hall measurements



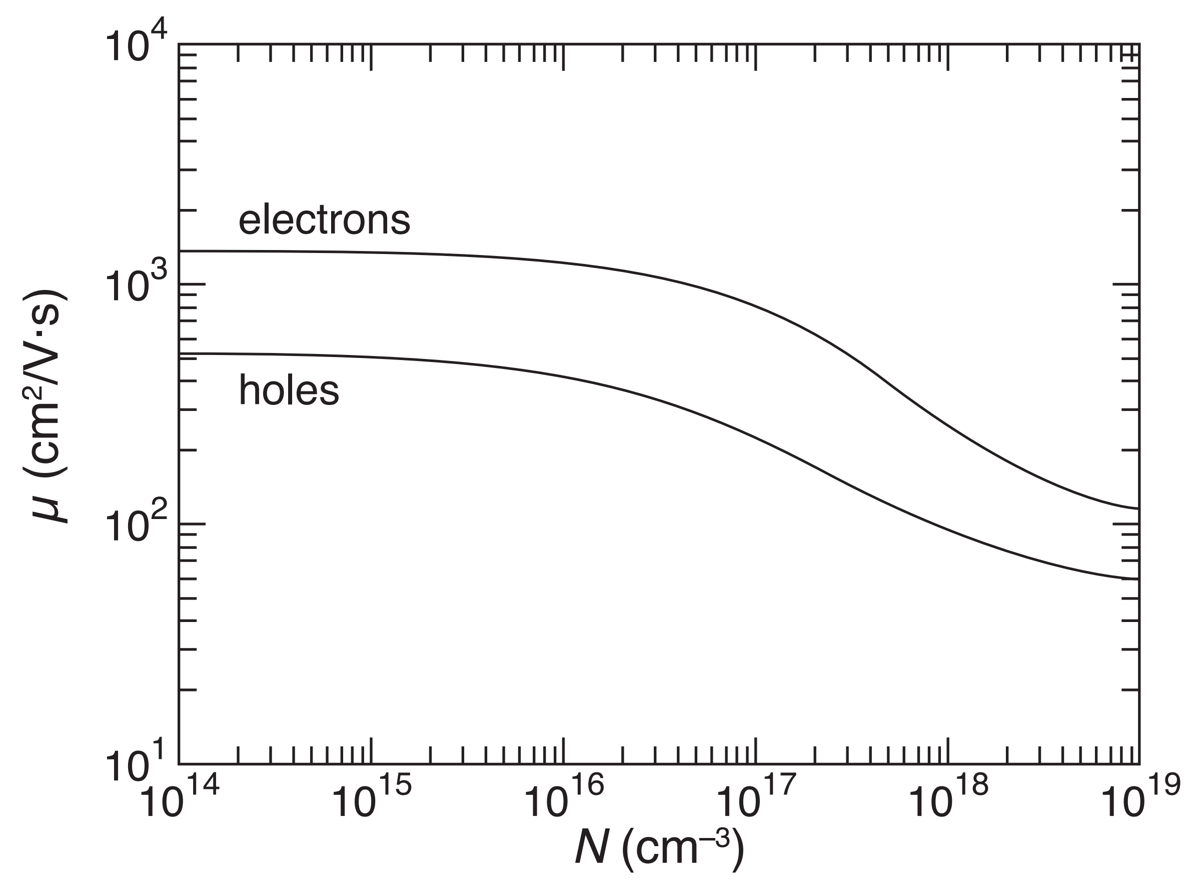
Optoelectronic properties

impurity (donor) band centered at 310 meV



Optoelectronic properties

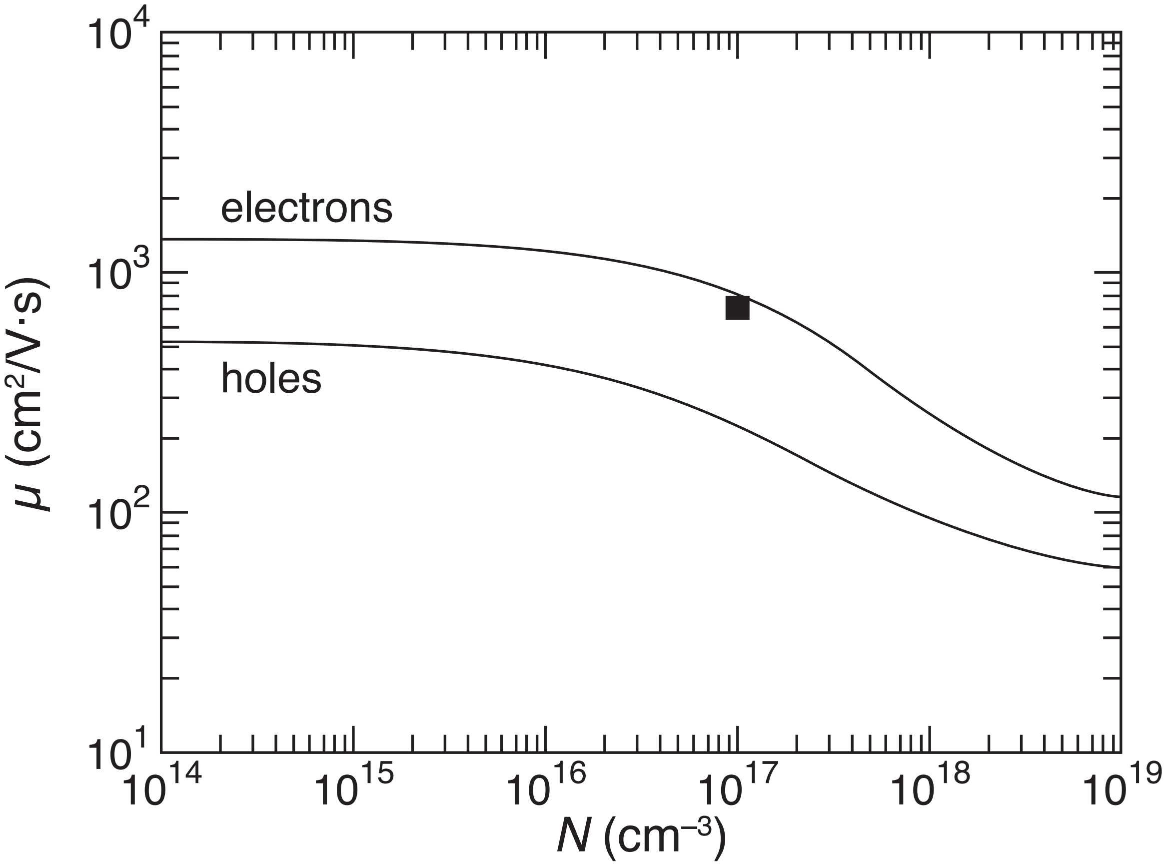
majority carrier mobility



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

Optoelectronic properties

majority carrier mobility



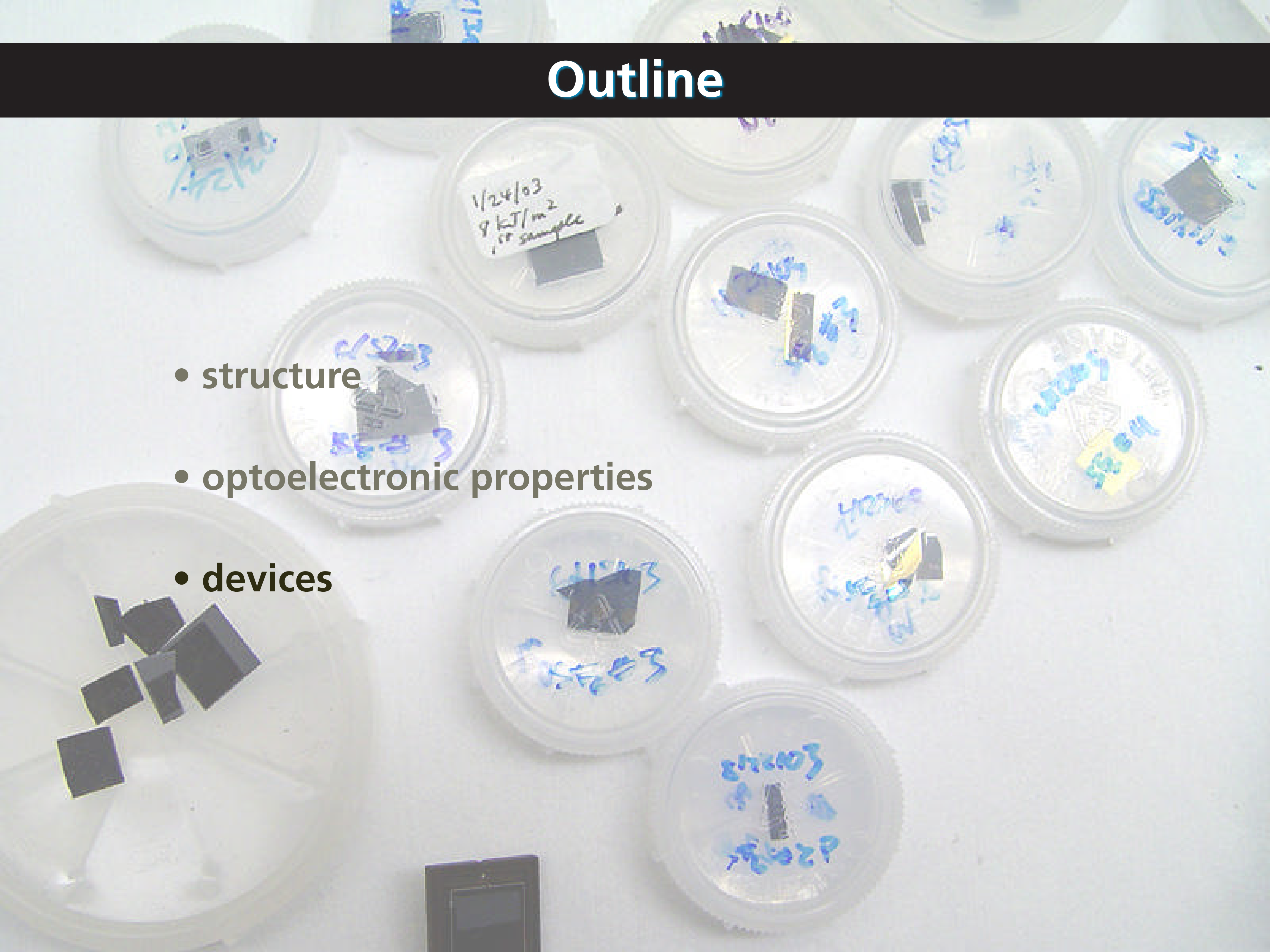
Caughey *et al.*, Proc. IEEE 55, 2192 (1967)

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

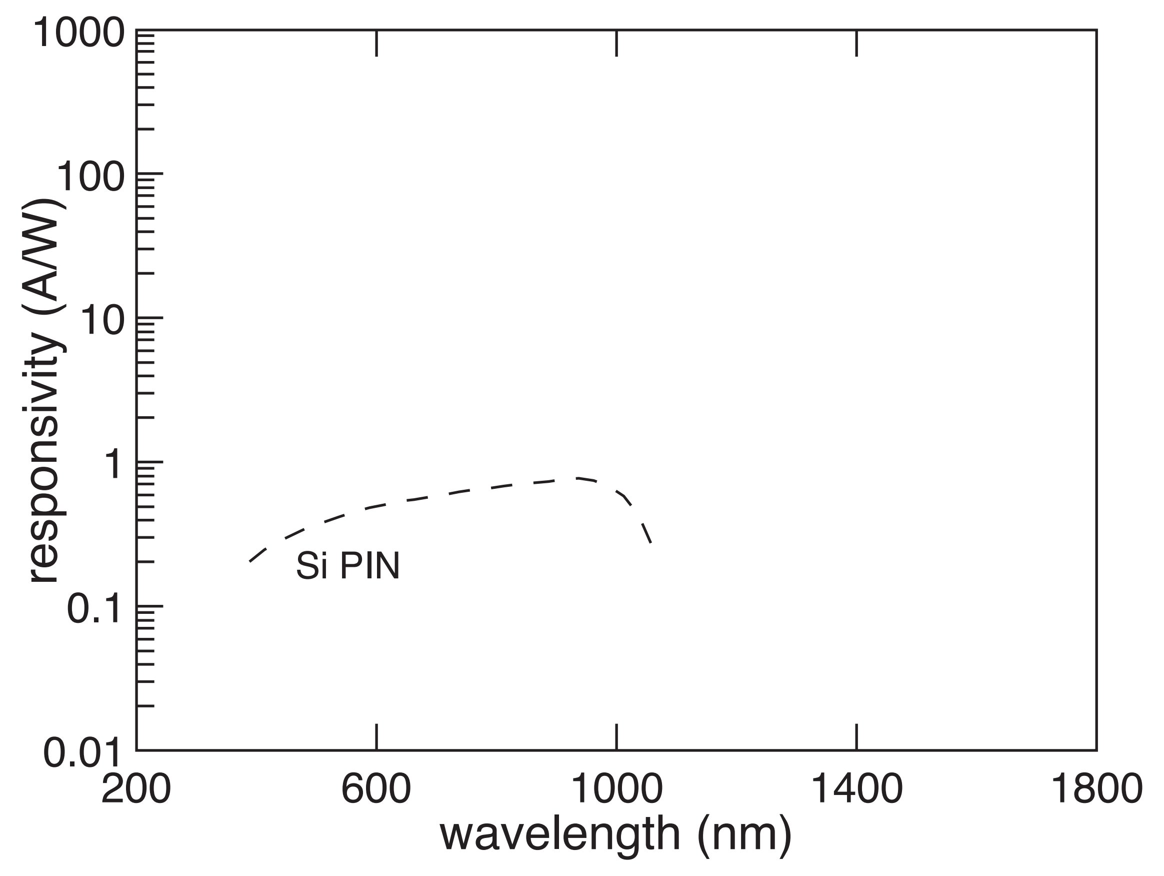
Outline



- structure
- optoelectronic properties
- **devices**

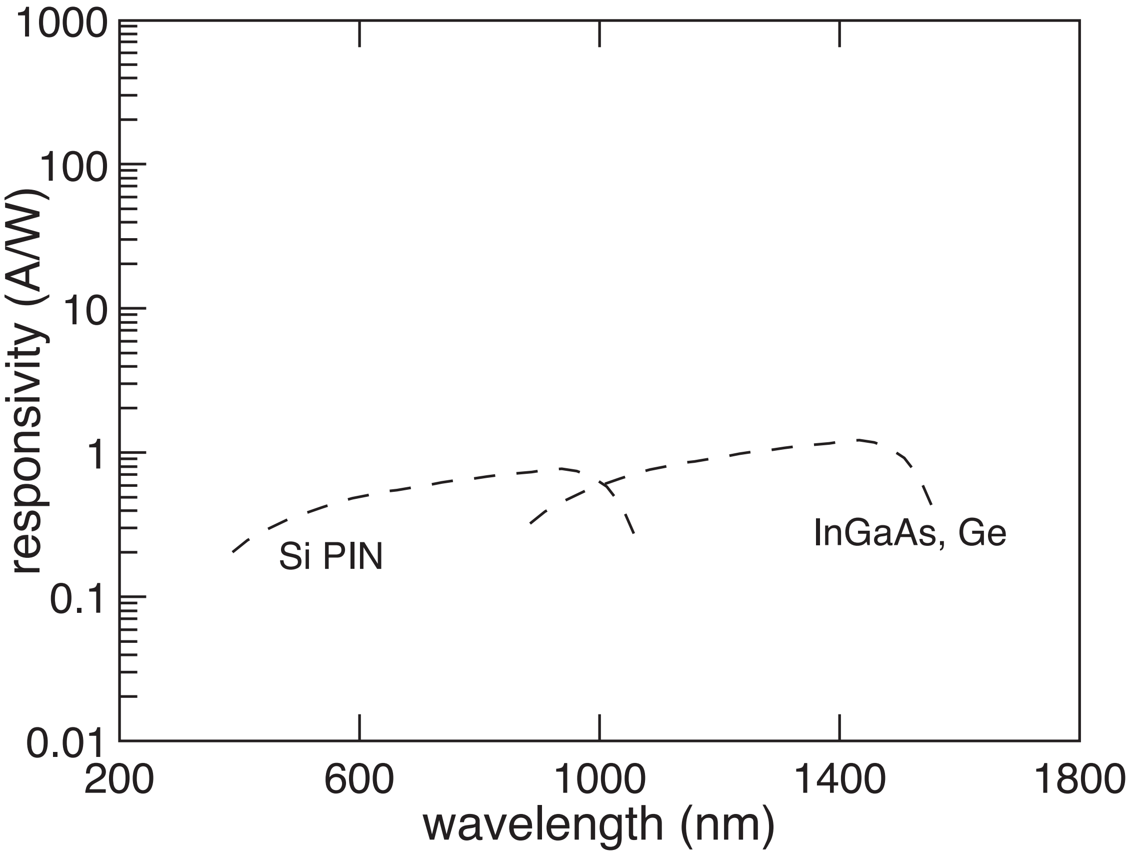
Devices

responsivity



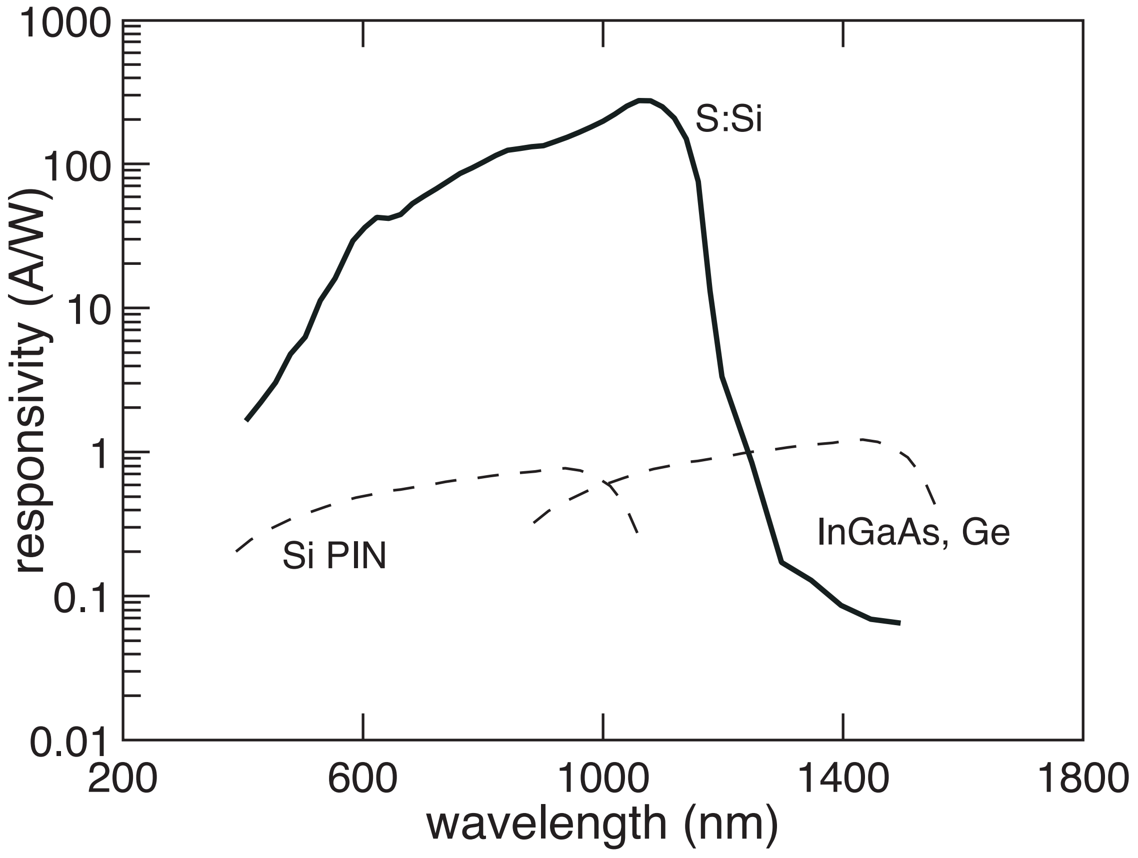
Devices

responsivity



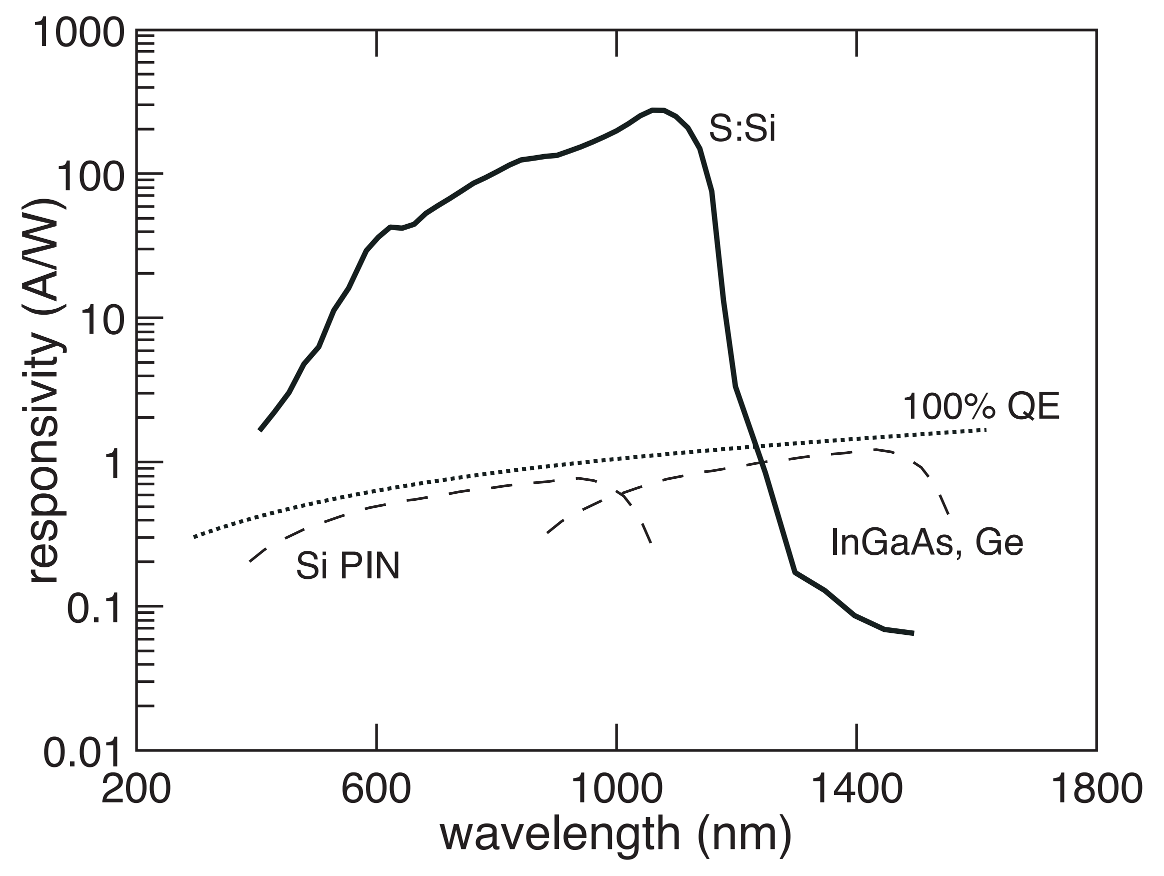
Devices

responsivity



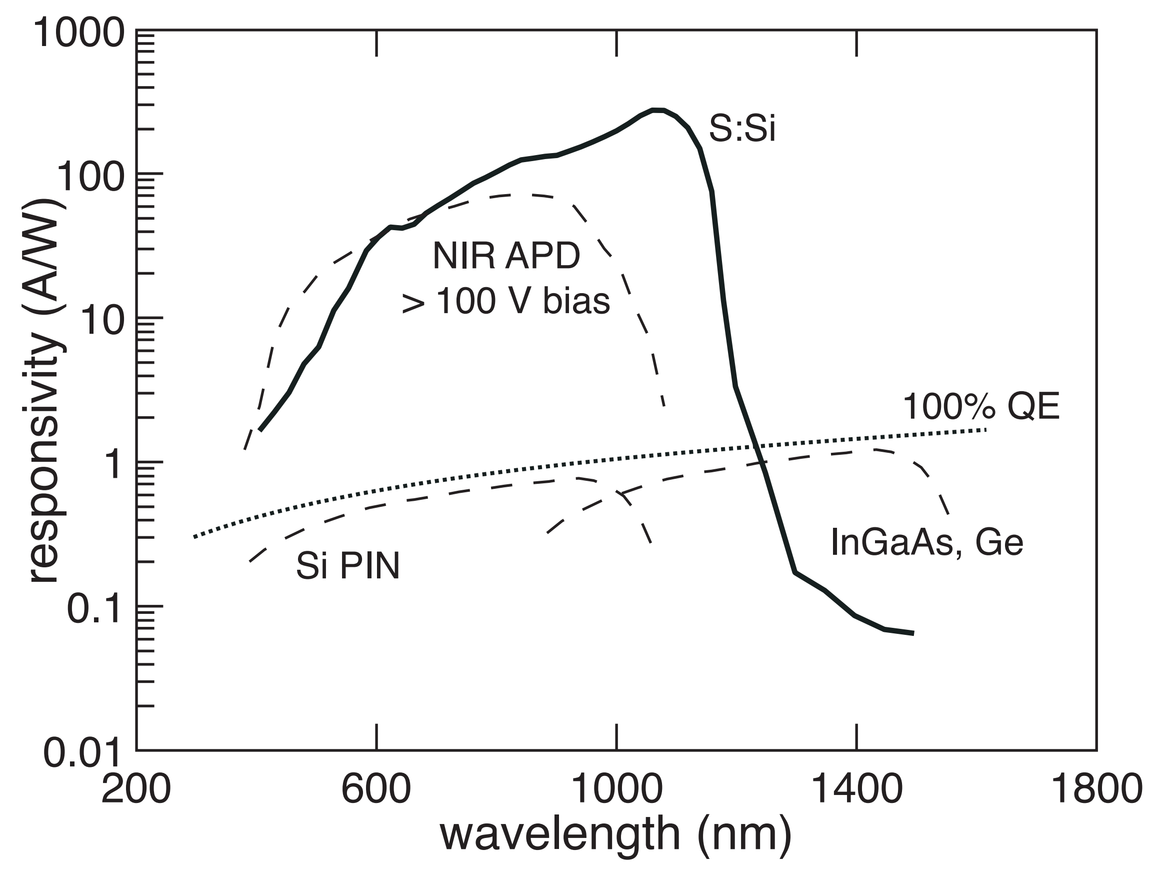
Devices

responsivity



Devices

responsivity

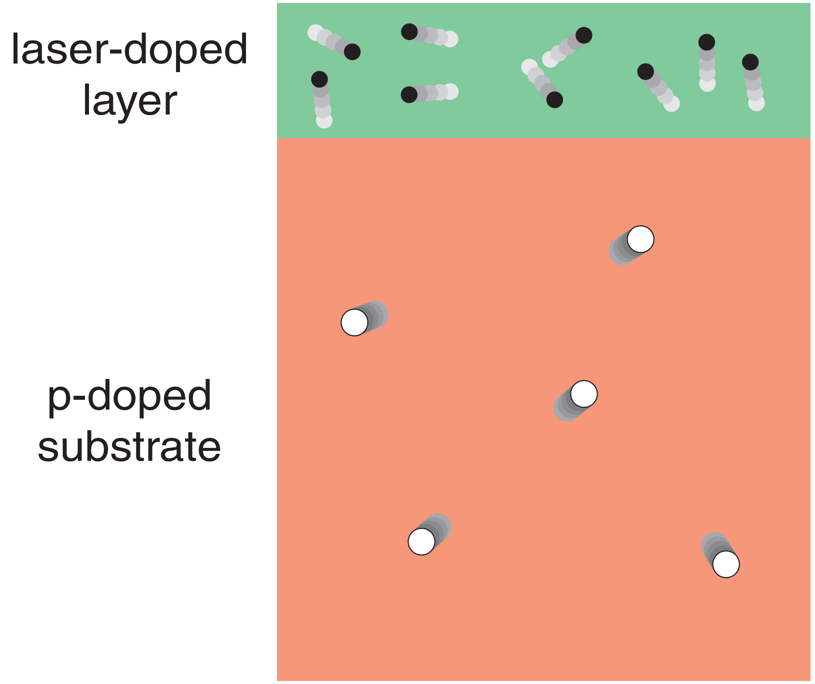


Devices

What causes gain?

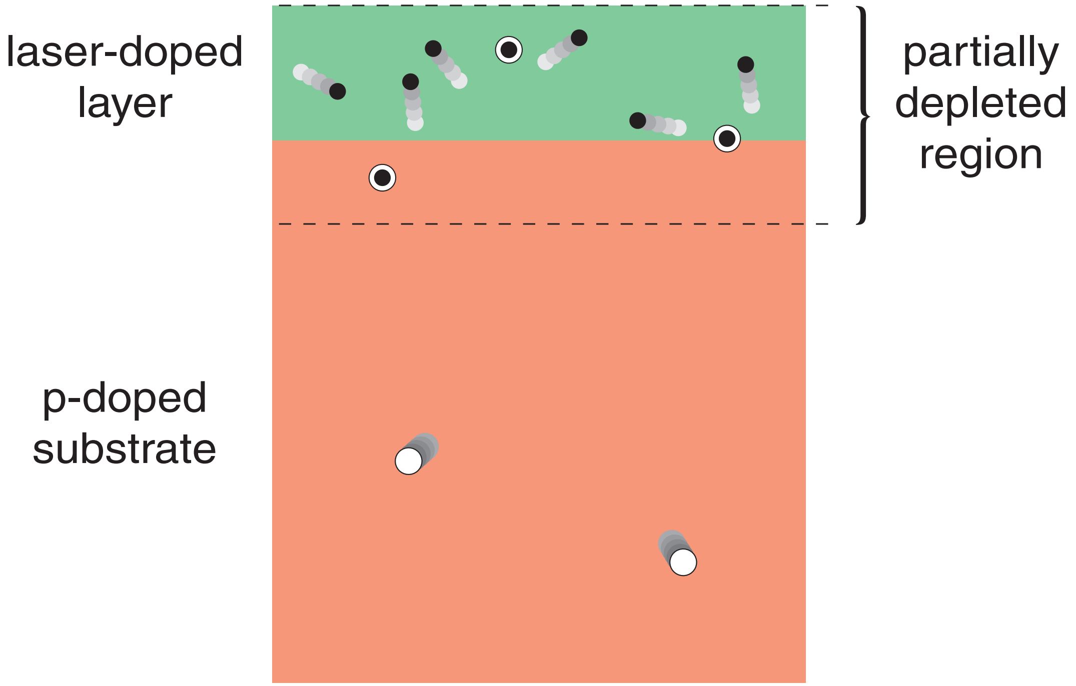
- impact excitation (avalanching)
- carrier lifetime >> transit time (photoconductive gain)
- some other mechanism

Devices



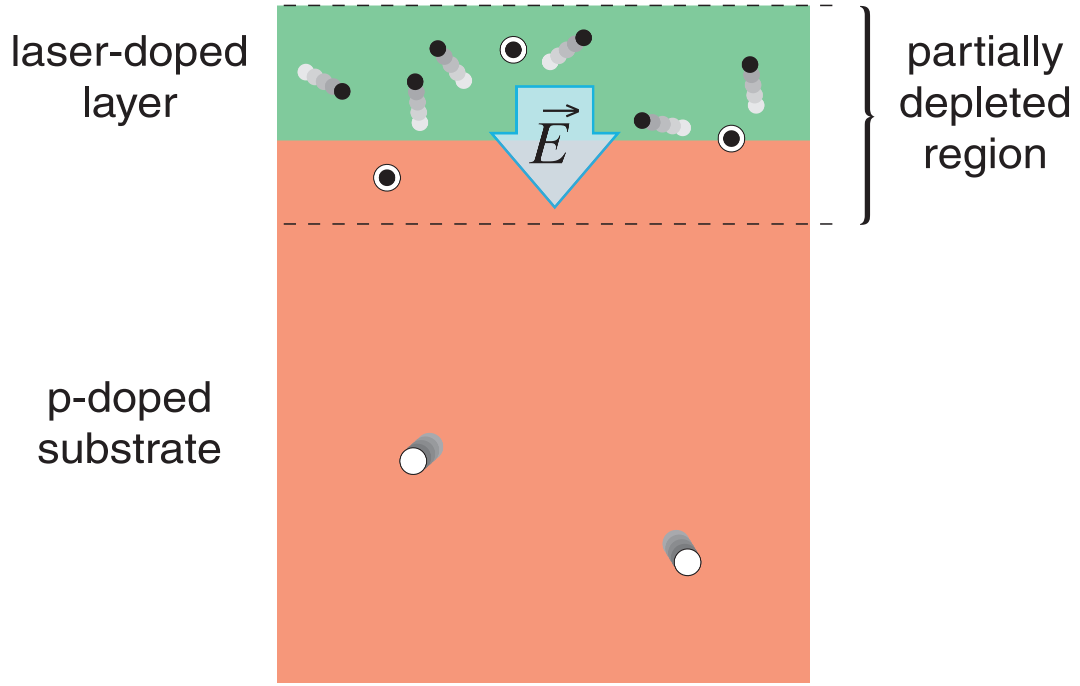
“pl junction”

Devices



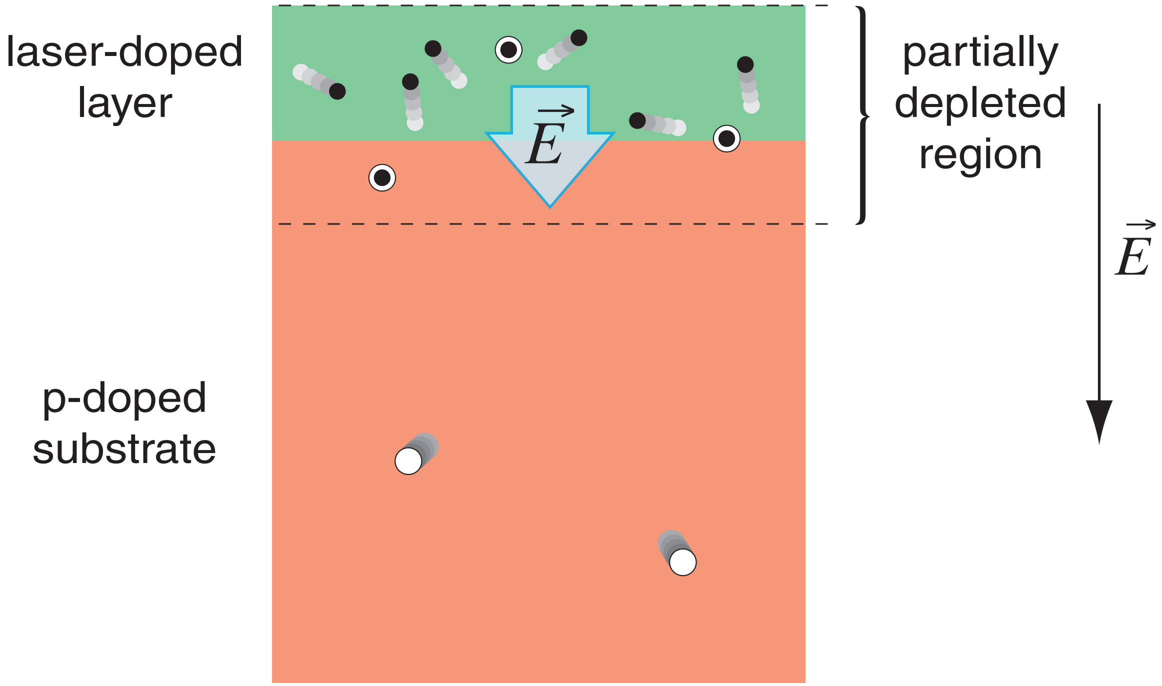
formation of partially depleted region

Devices



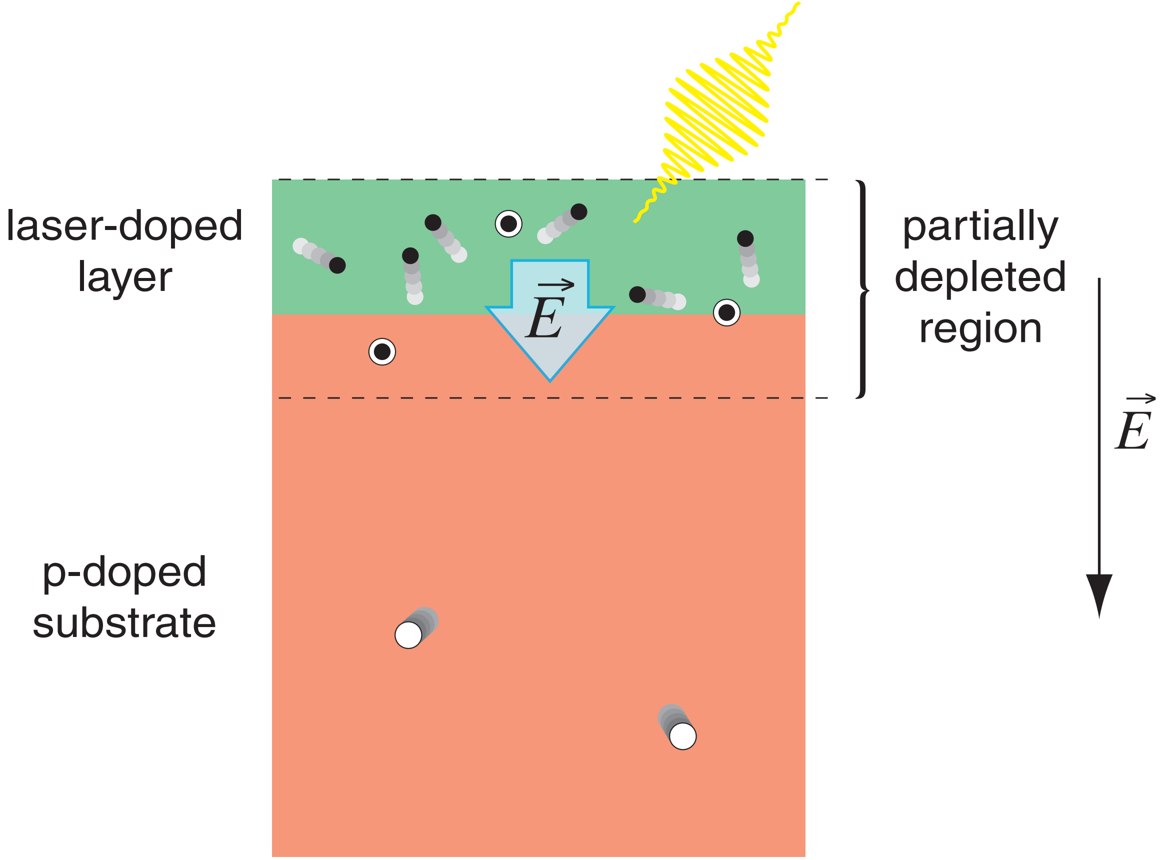
formation of partially depleted region

Devices



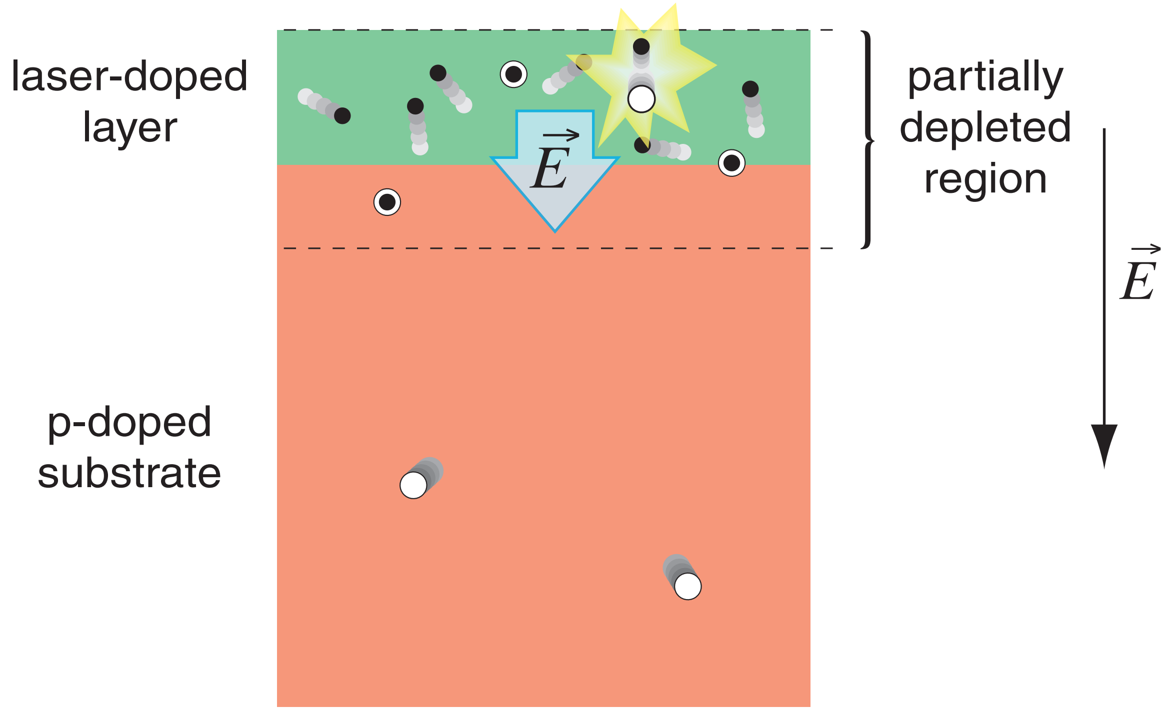
apply backward bias…

Devices



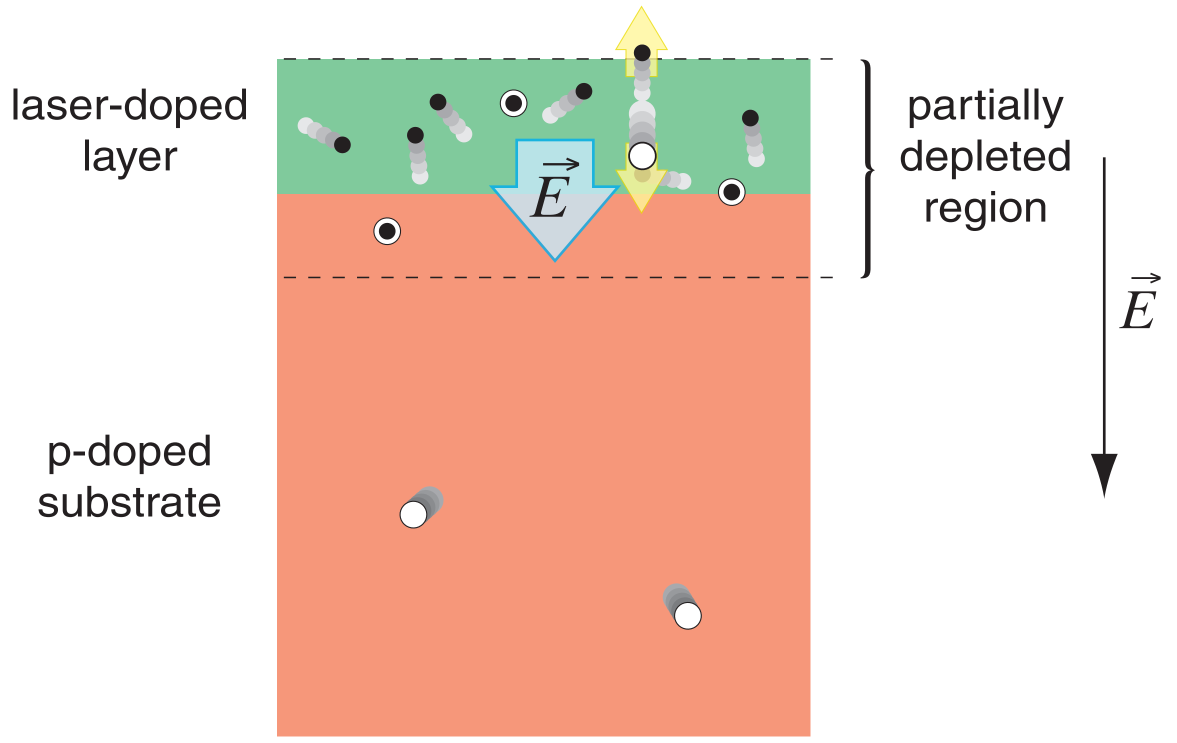
…incident photon generates electron-hole pair…

Devices



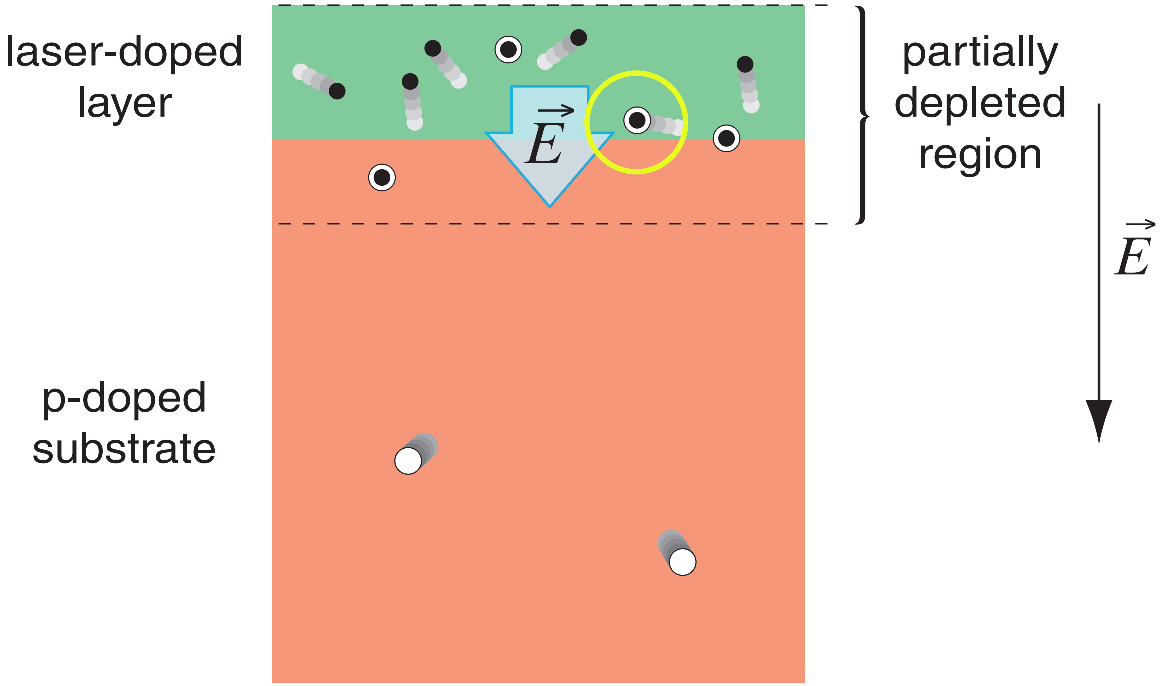
…incident photon generates electron-hole pair…

Devices



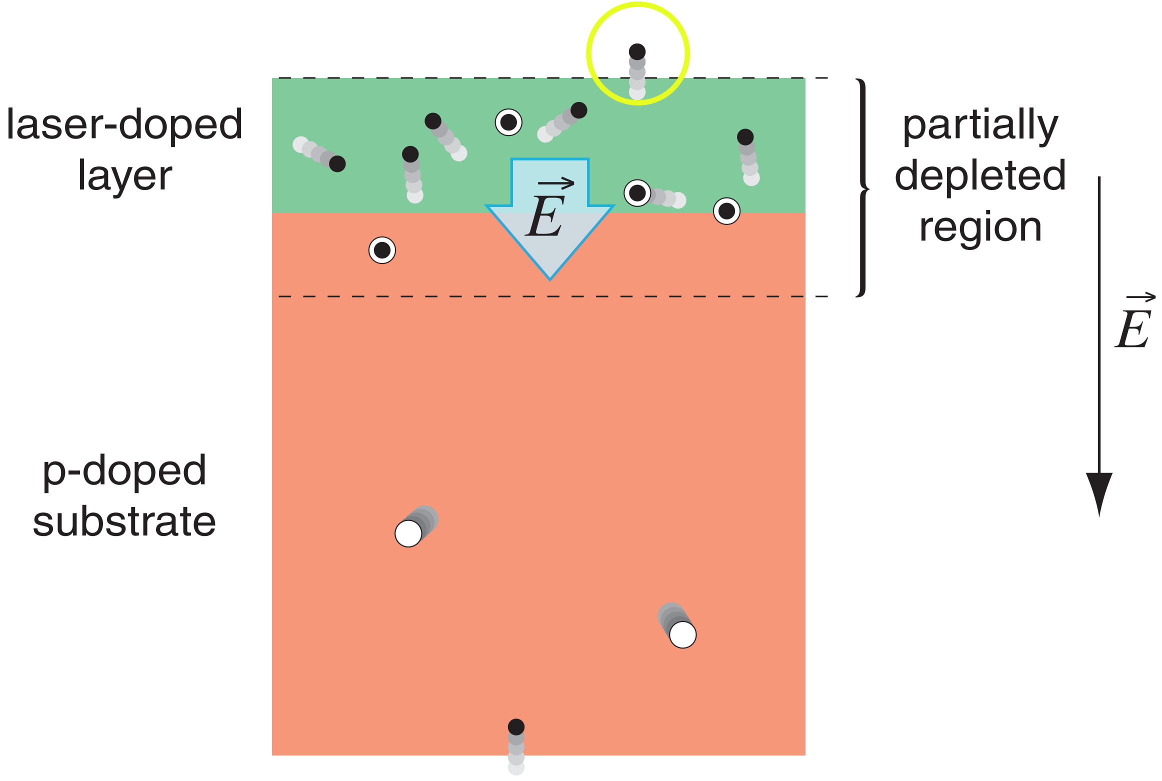
…carriers accelerate away from each other…

Devices



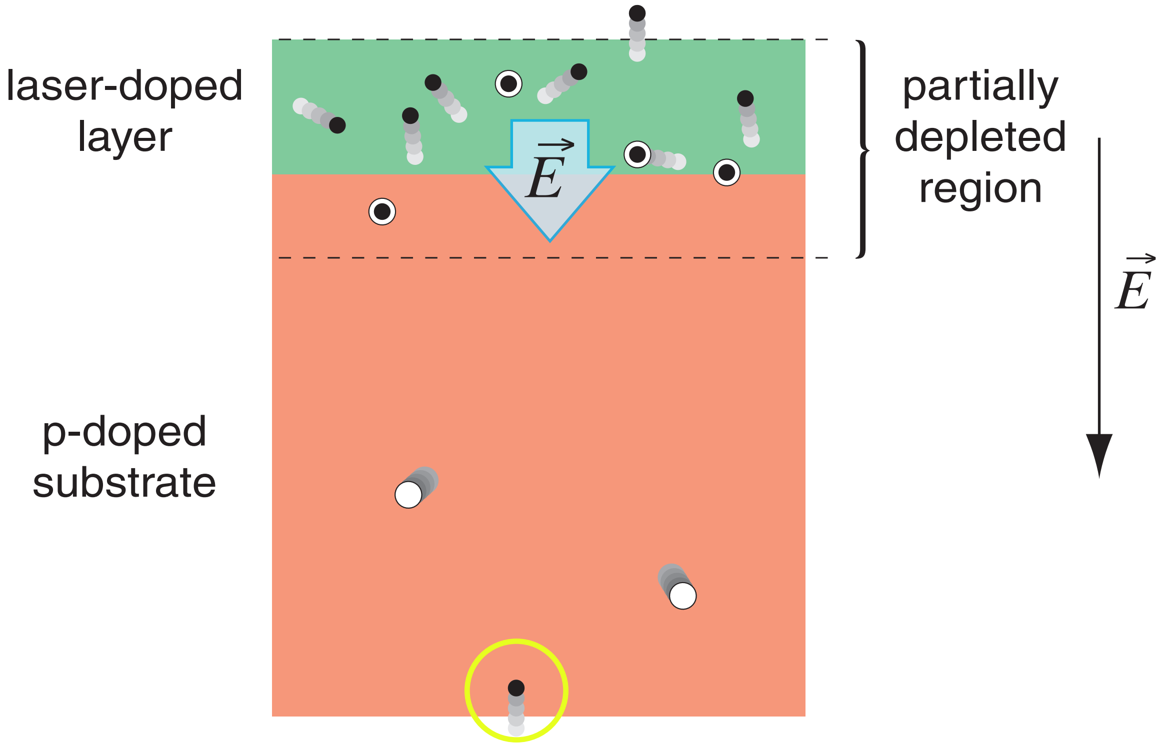
…hole is trapped

Devices



meanwhile electron exits sample…

Devices



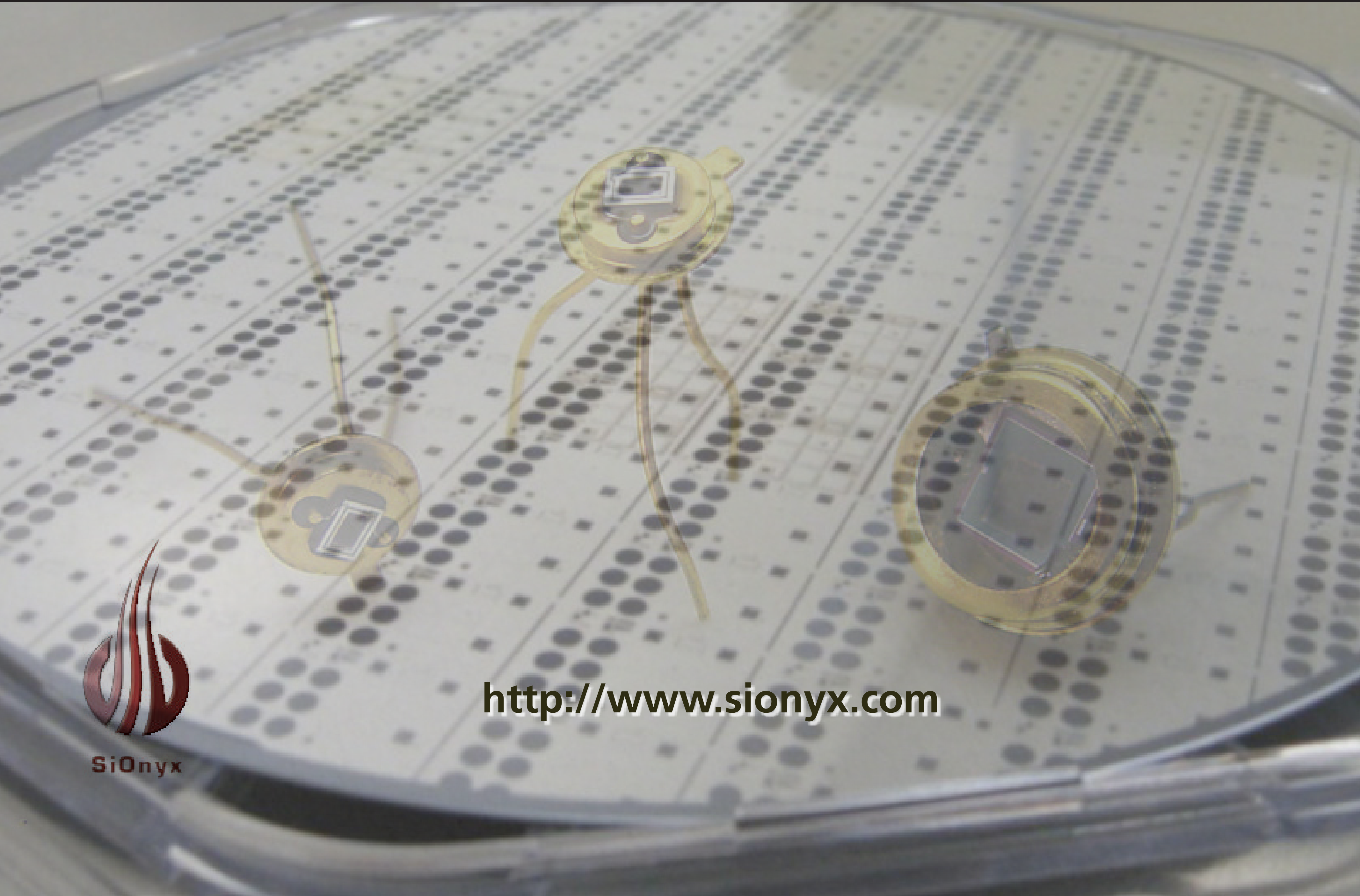
…and source provides new electron

Devices

Things to keep in mind

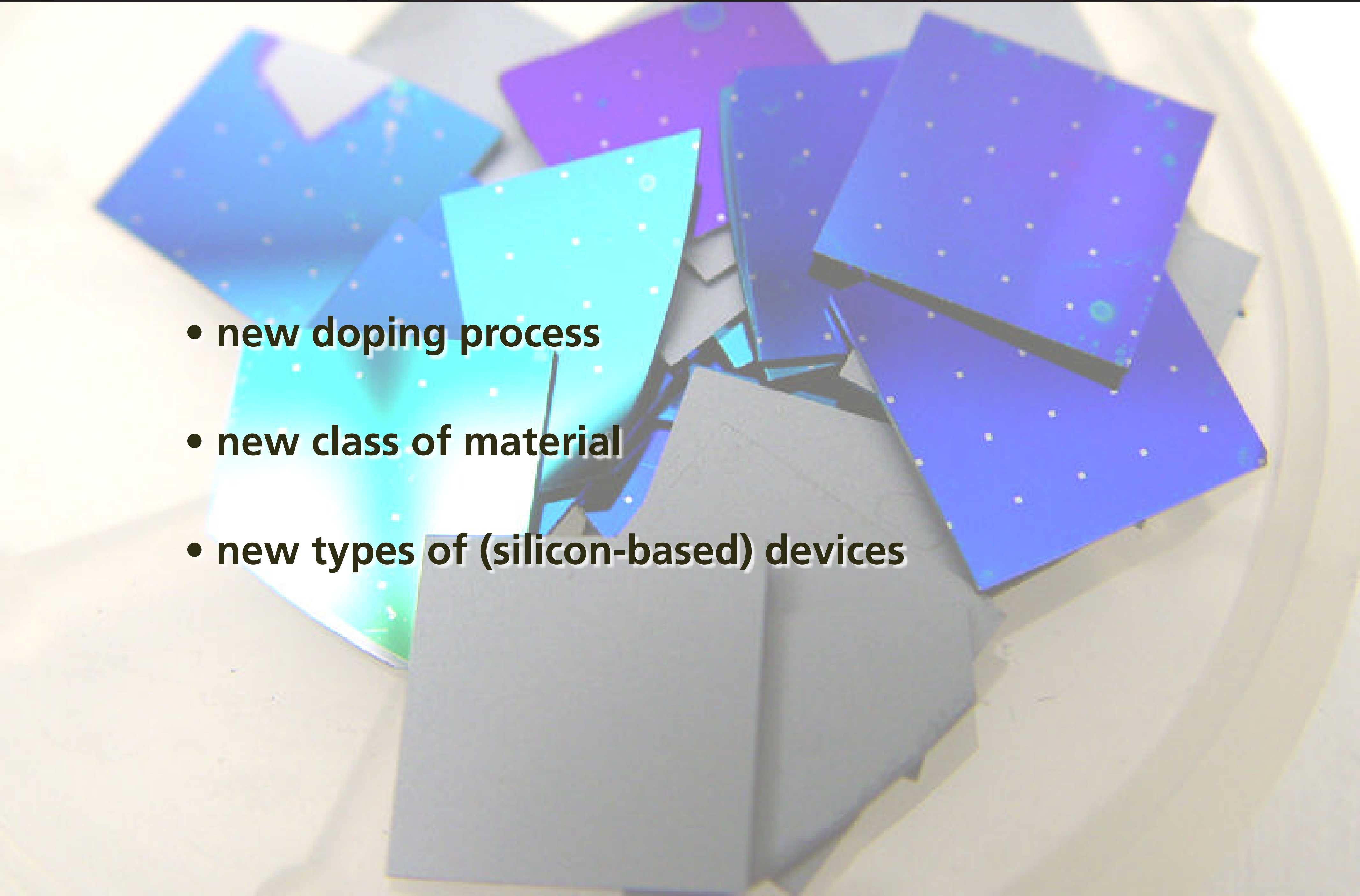
- can turn absorption into carrier generation
- very high responsivity in VIS and IR
- phenomenal photoconductive gain

Devices



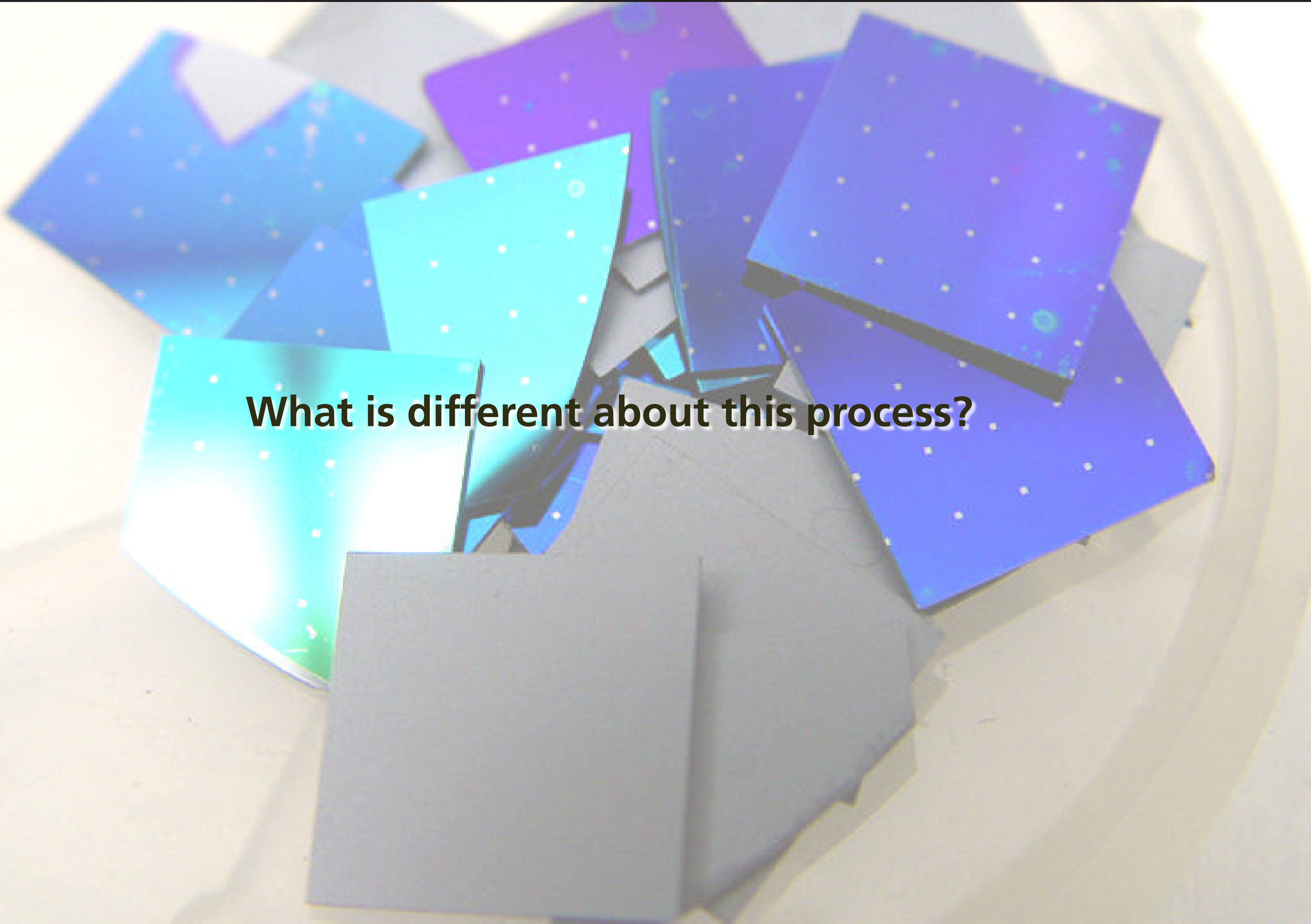
http://www.sionyx.com

Conclusion



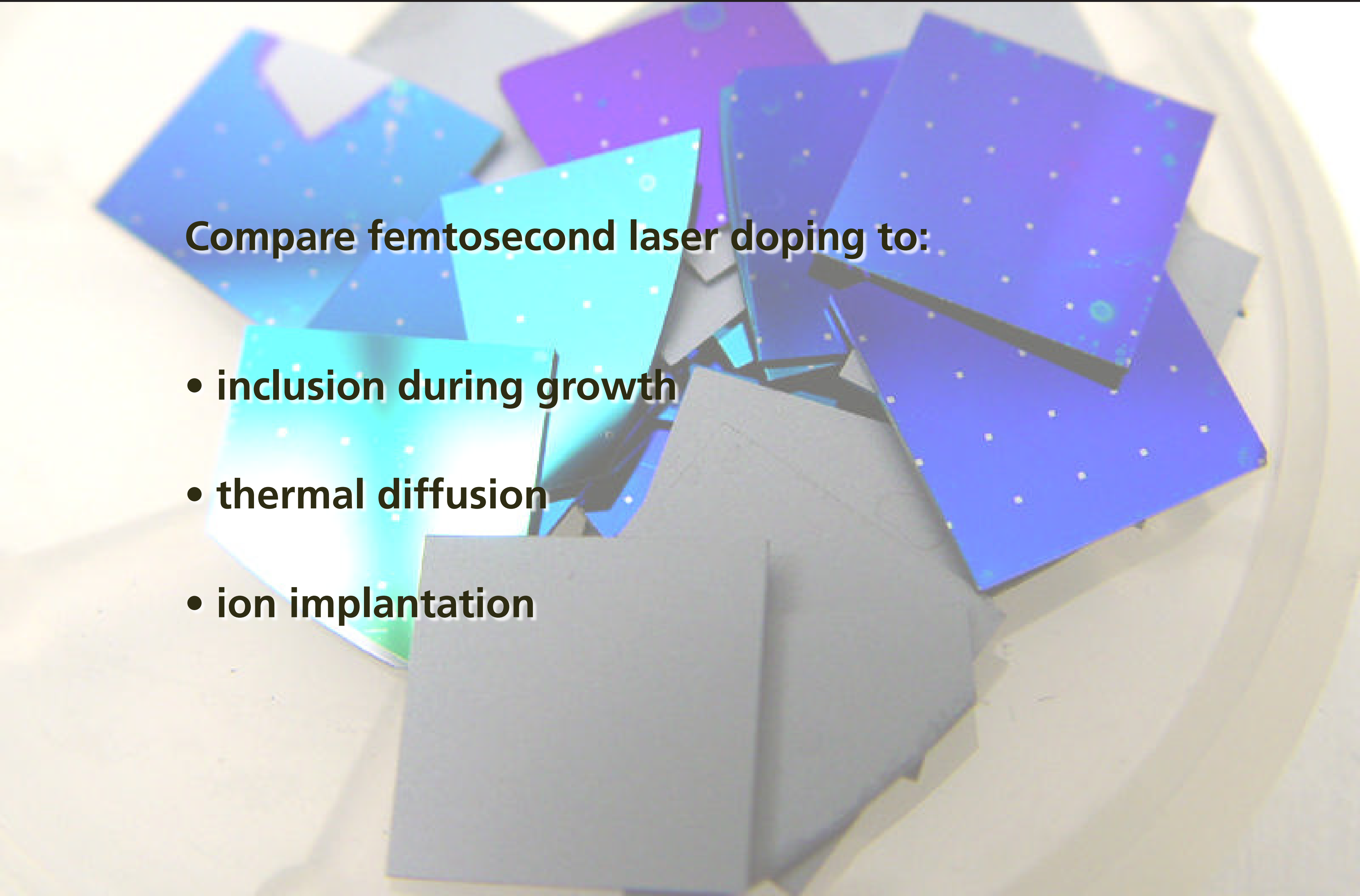
- new doping process
- new class of material
- new types of (silicon-based) devices

Conclusion



What is different about this process?

Conclusion



Compare femtosecond laser doping to:

- inclusion during growth
- thermal diffusion
- ion implantation


MAZUR GROUP

Funding:

Army Research Office
DARPA
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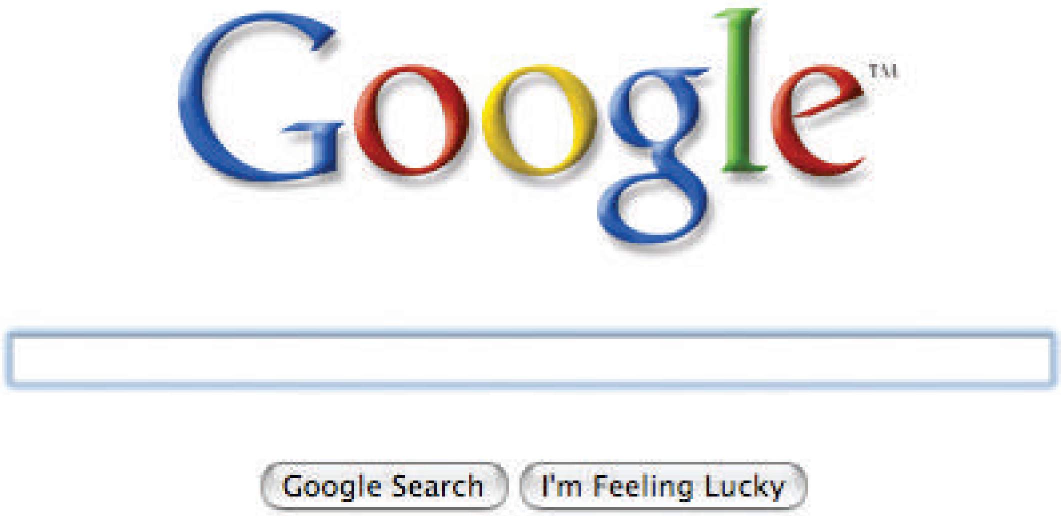
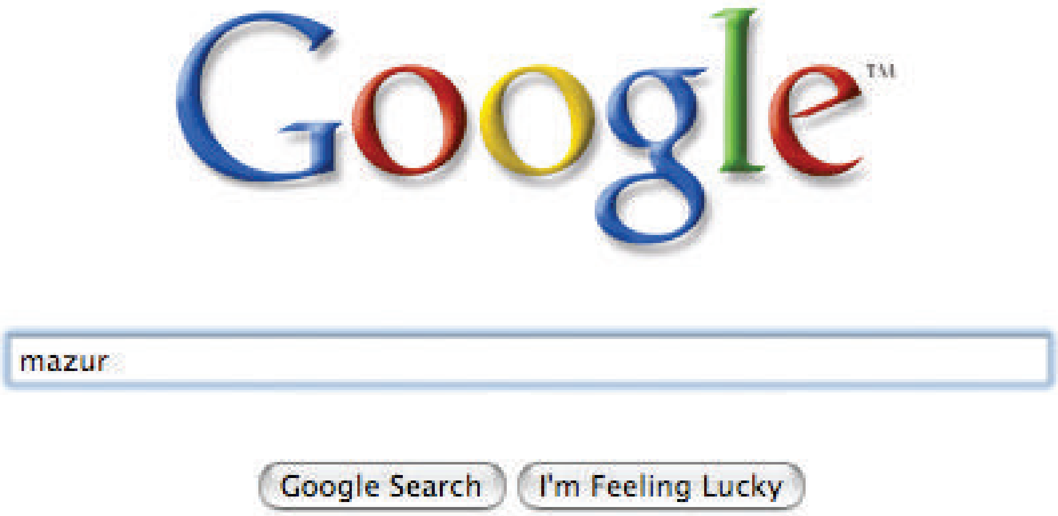
NDSEG
National Science Foundation

for more information:

http://mazur-www.harvard.edu


Google™
Google Search
I'm Feeling Lucky



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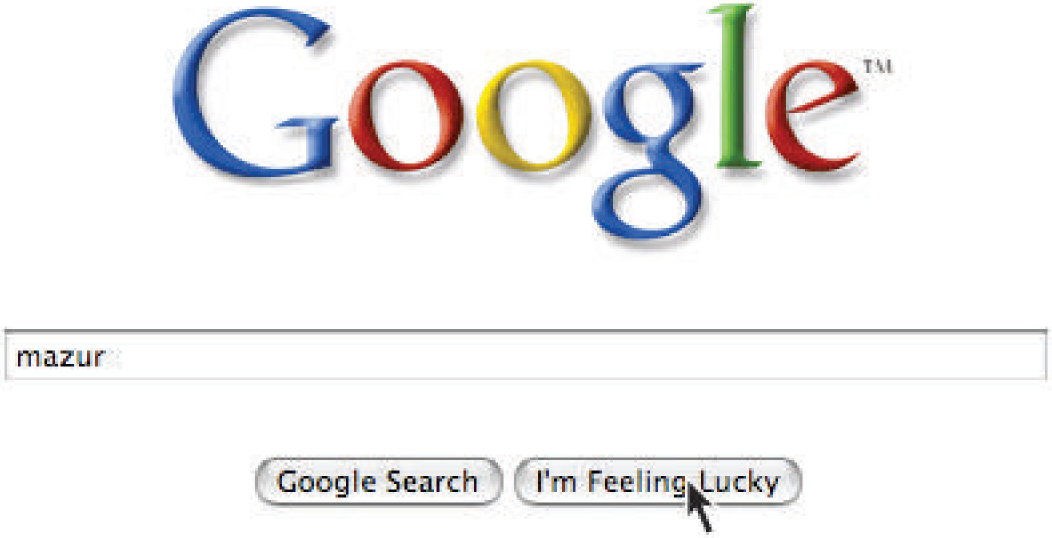

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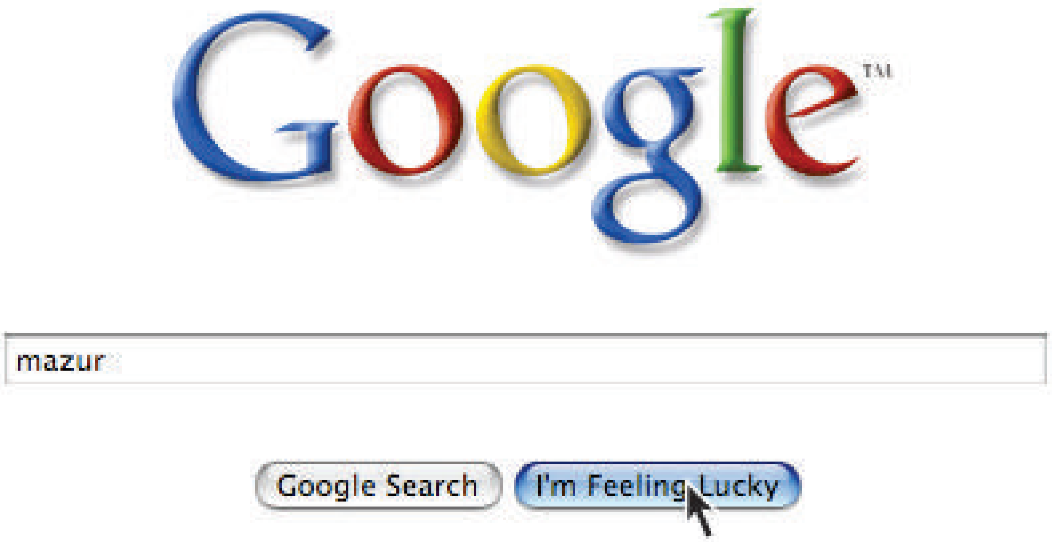

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