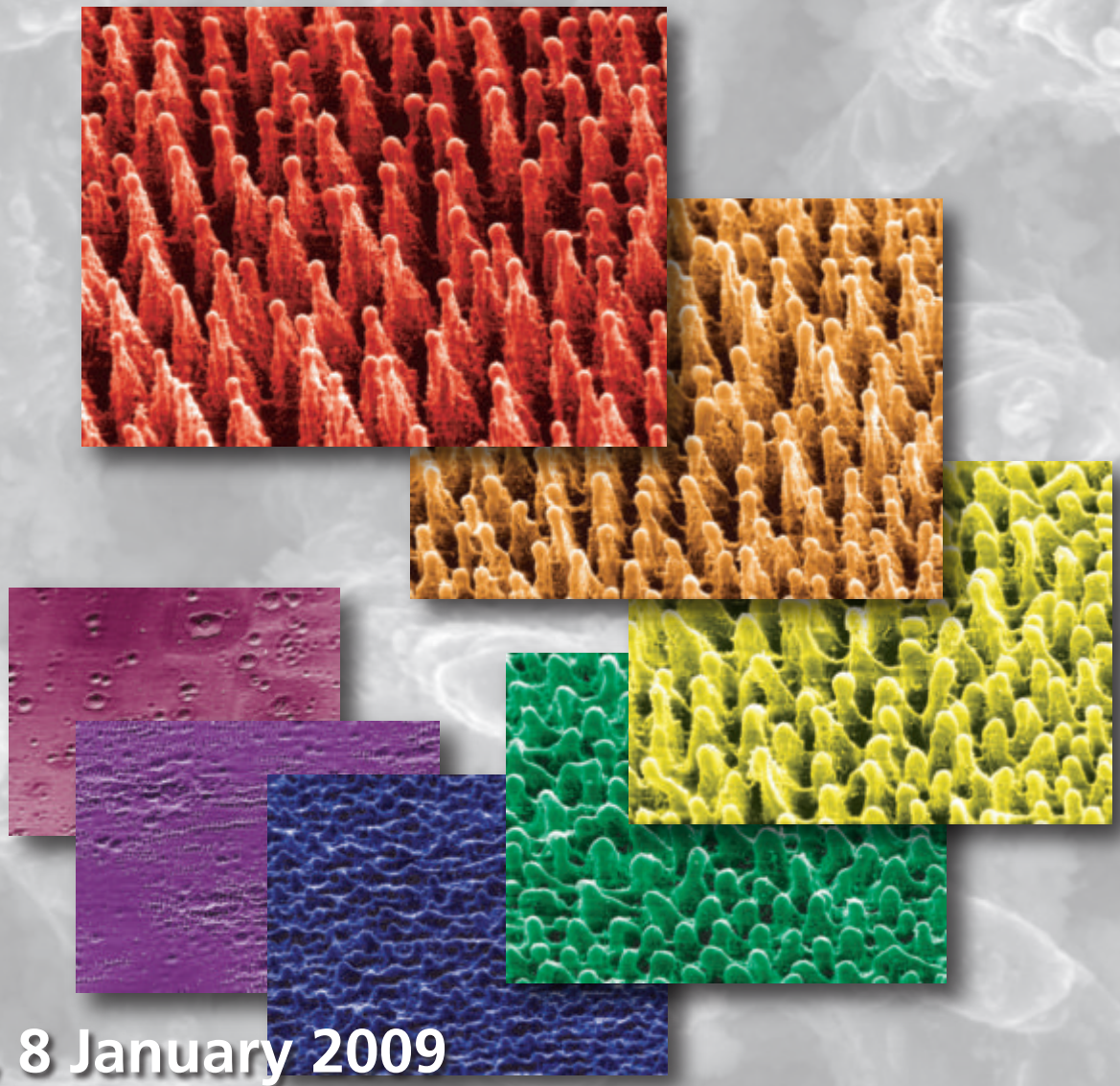
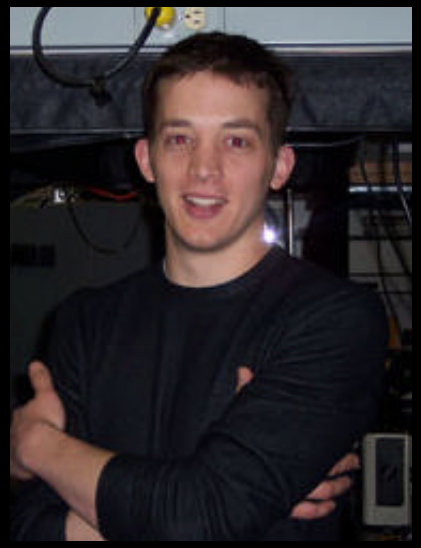
Optically hyperdoped semiconductors



PQE 2009
Snowbird, UT, 8 January 2009

Eric Mazur



Mark Winkler

Eric Diebold

Brian Tull

and also....

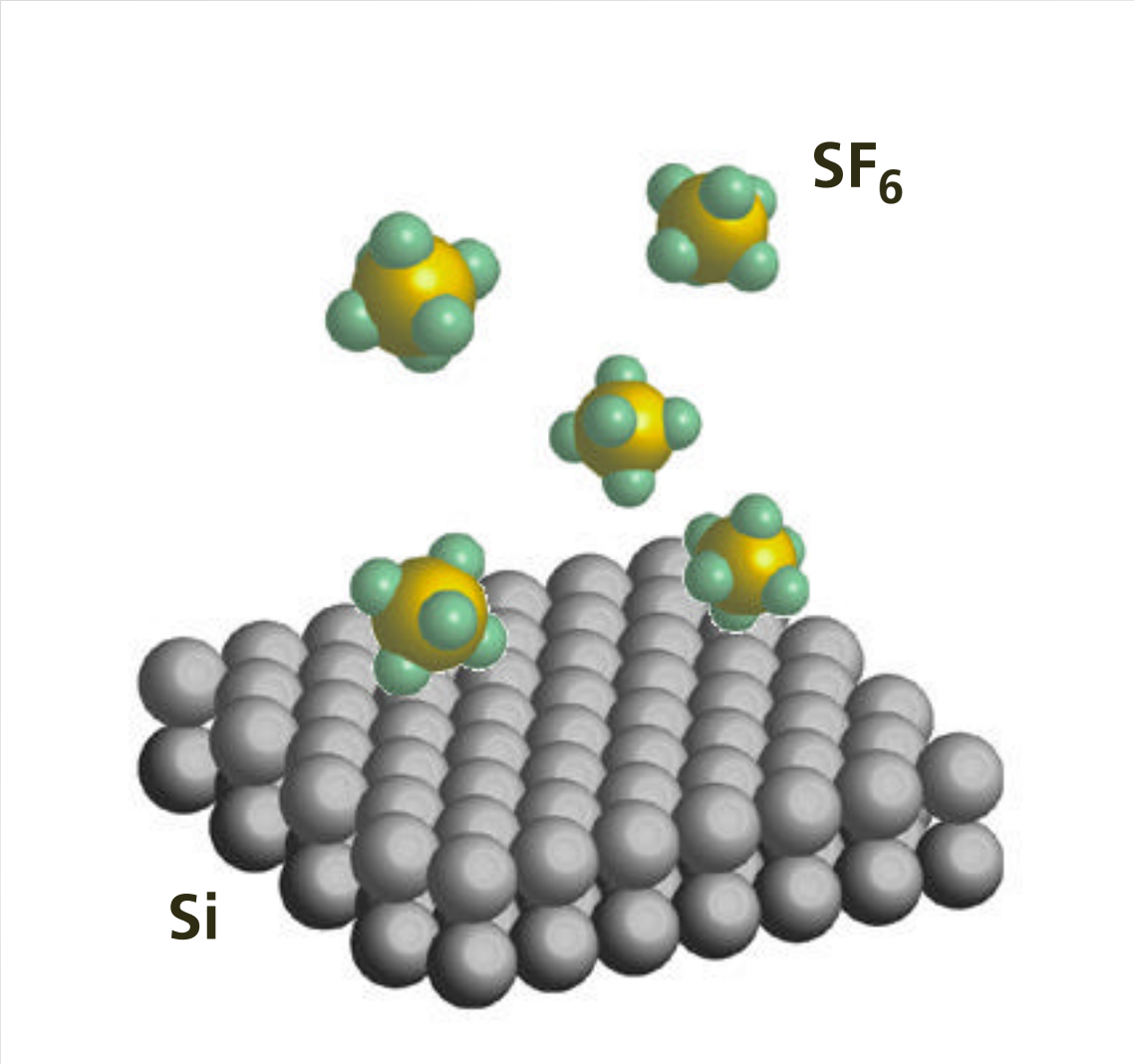
Dr. Jim Carey
Dr. Tsing-Hua Her
Dr. Shrenik Deliwala
Dr. Richard Finlay
Dr. Michael Sheehy
Dr. Jeffrey Warrander
Dr. Claudia Wu
Dr. Rebecca Younkin
Prof. Catherine Crouch
Prof. Mengyan Shen

Dr. John Chervinsky
Dr. Joshua Levinson

Prof. Tonio Buonassisi (MIT)
Dr. François Génin (LLNL)
Dr. Richard Farrell
Dr. Arieh Karger (RMD)
Dr. Richard Meyers (RMD)

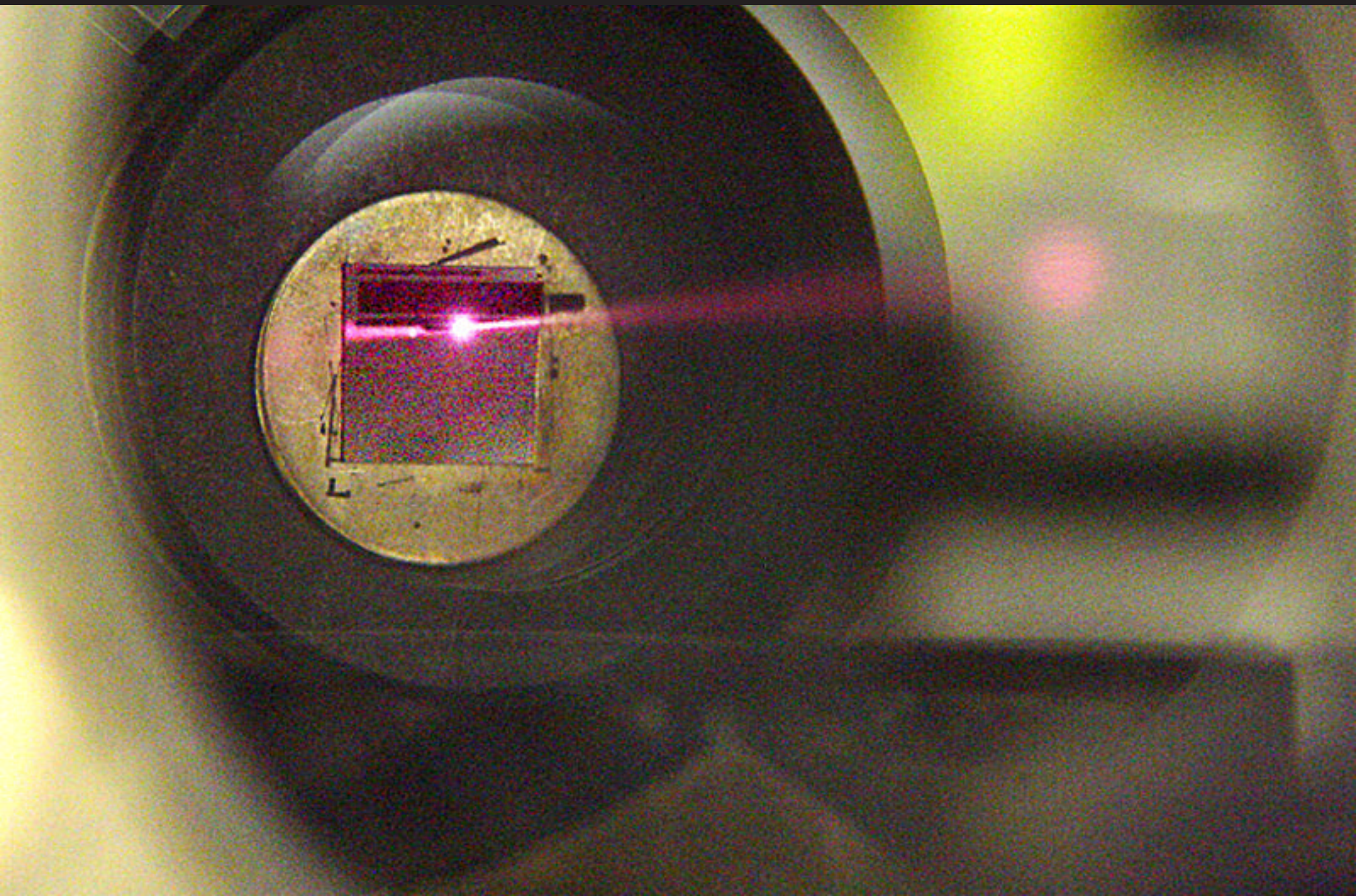
Prof. Michael Aziz
Prof. Cynthia Friend
Prof. Li Zhao (Fudan)

Introduction

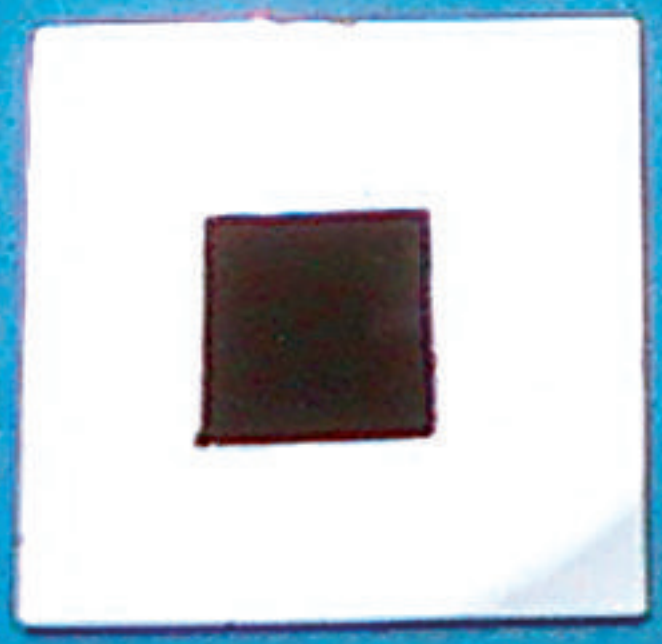


irradiate with 100-fs 10 kJ/m^2 pulses

Introduction

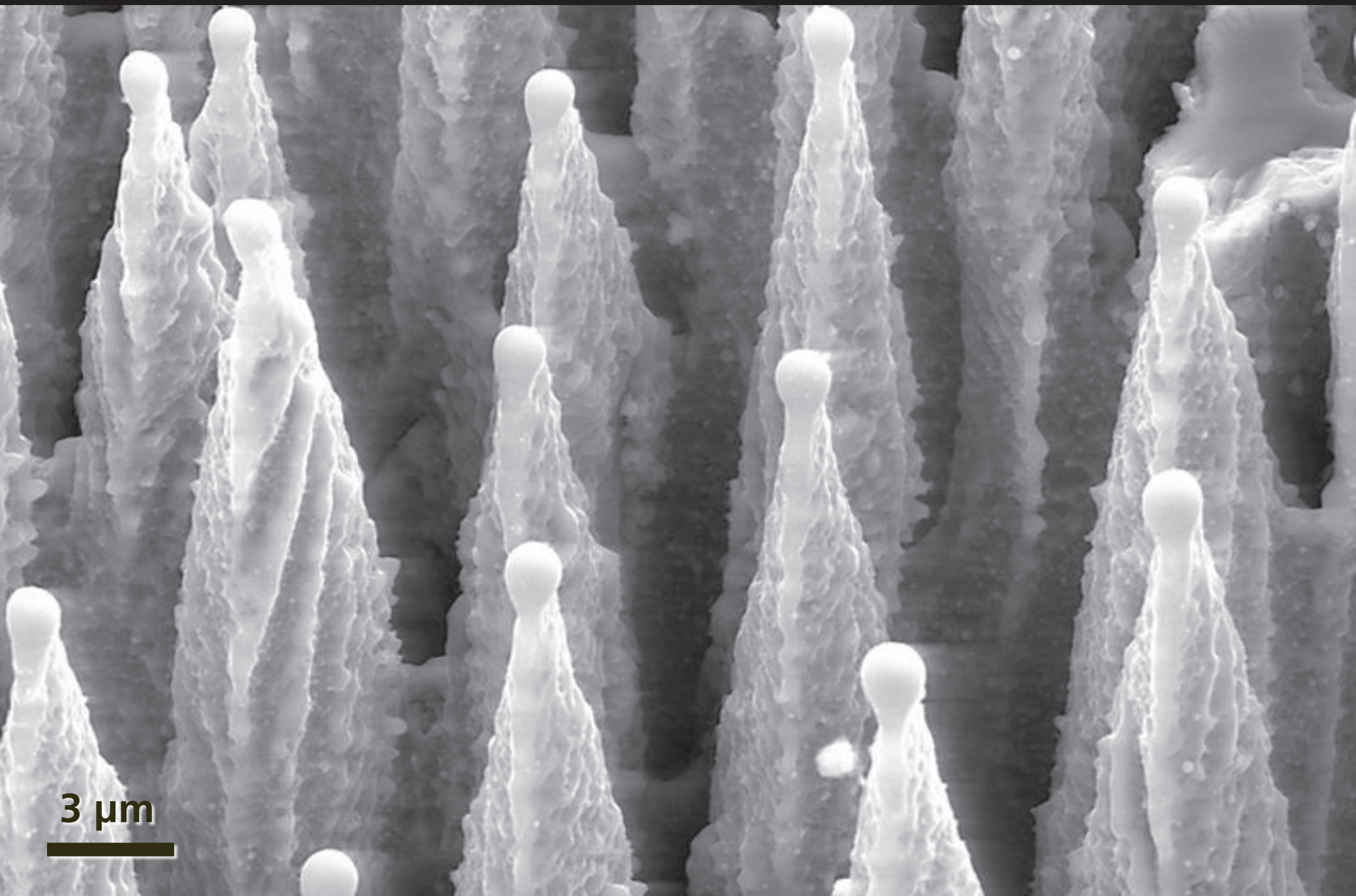


Introduction



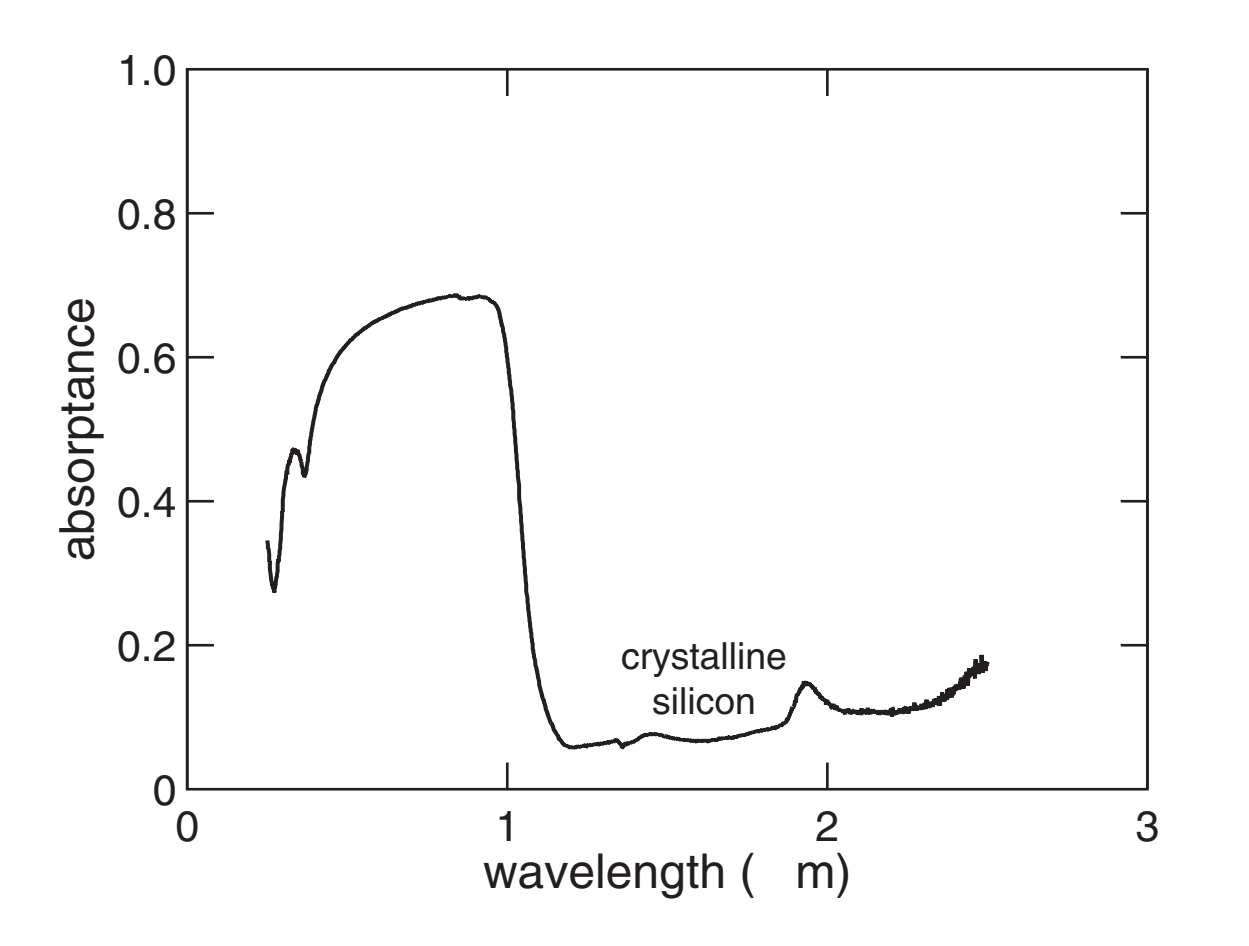
“black silicon”

Introduction



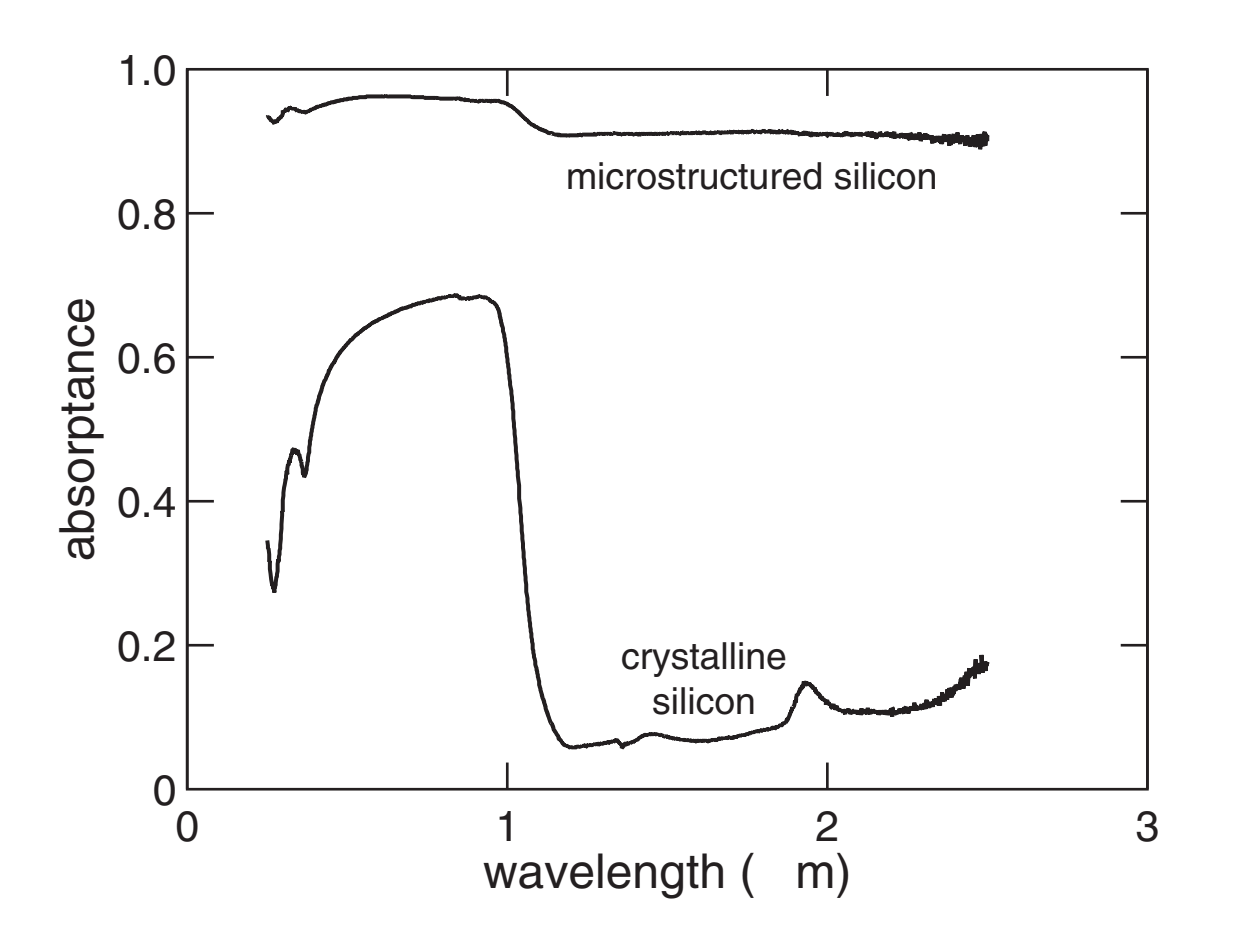
Introduction

absorptance (1 – *R* – *T*)

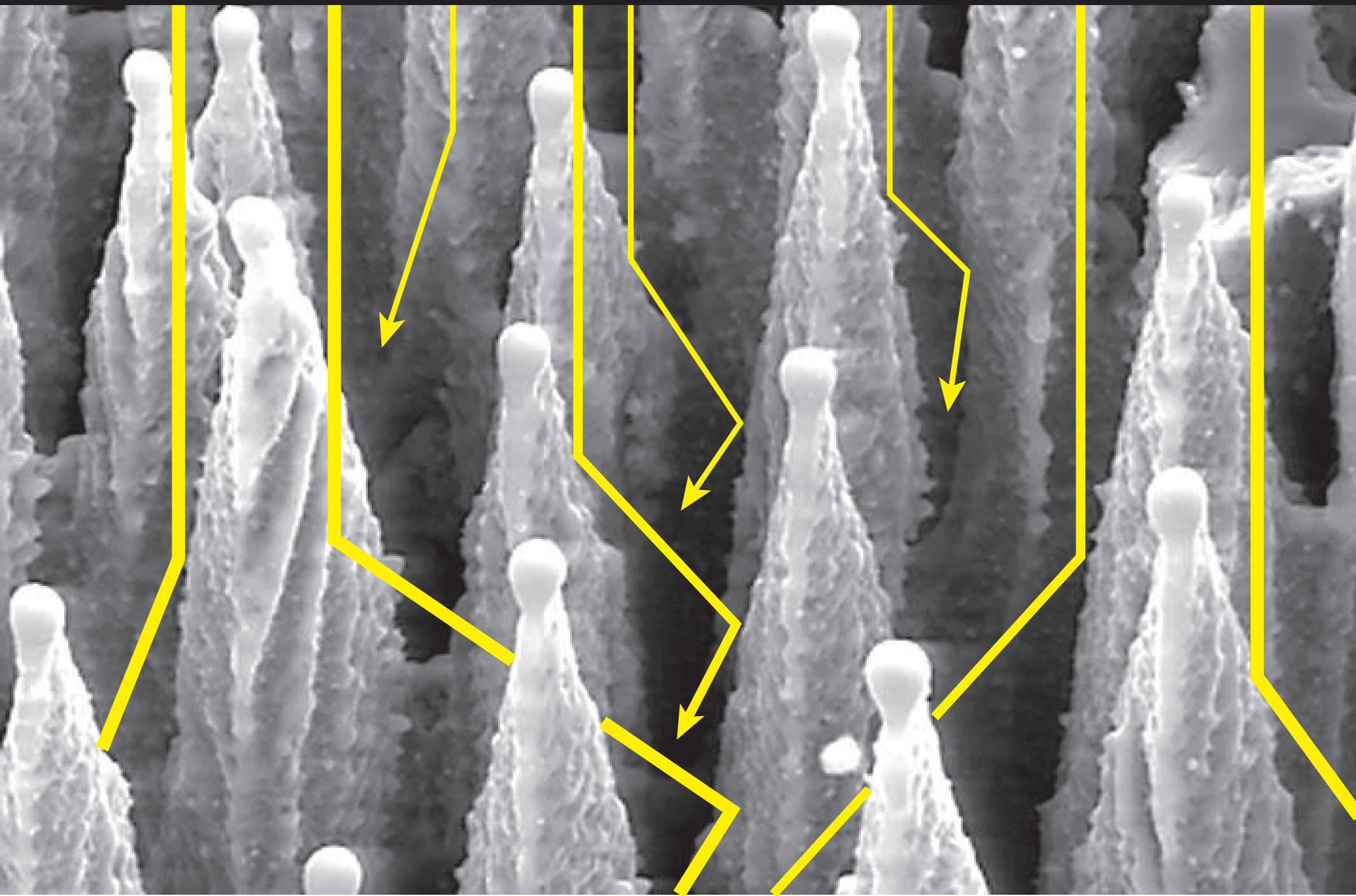


Introduction

absorptance (1 – *R* – *T*)

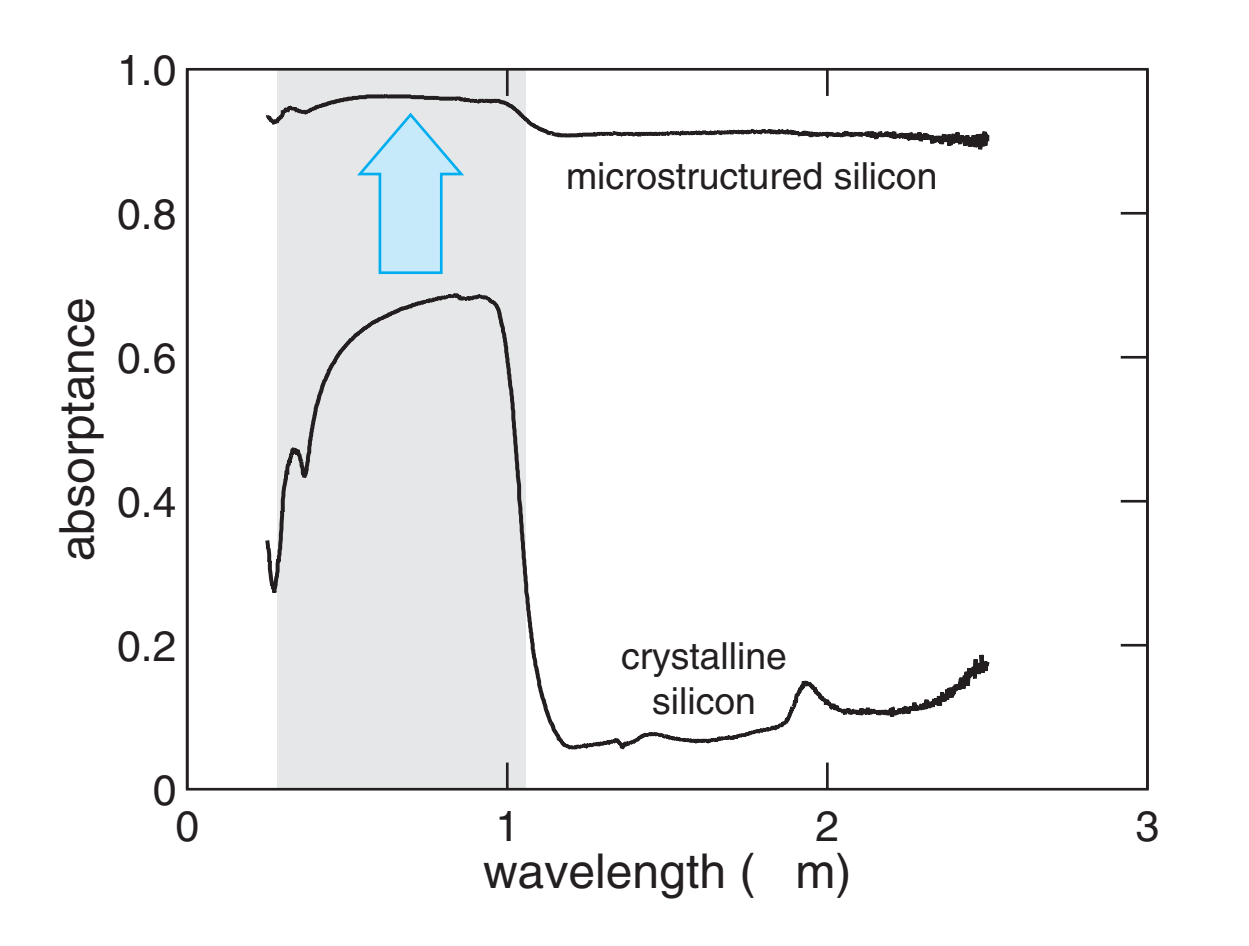


Introduction



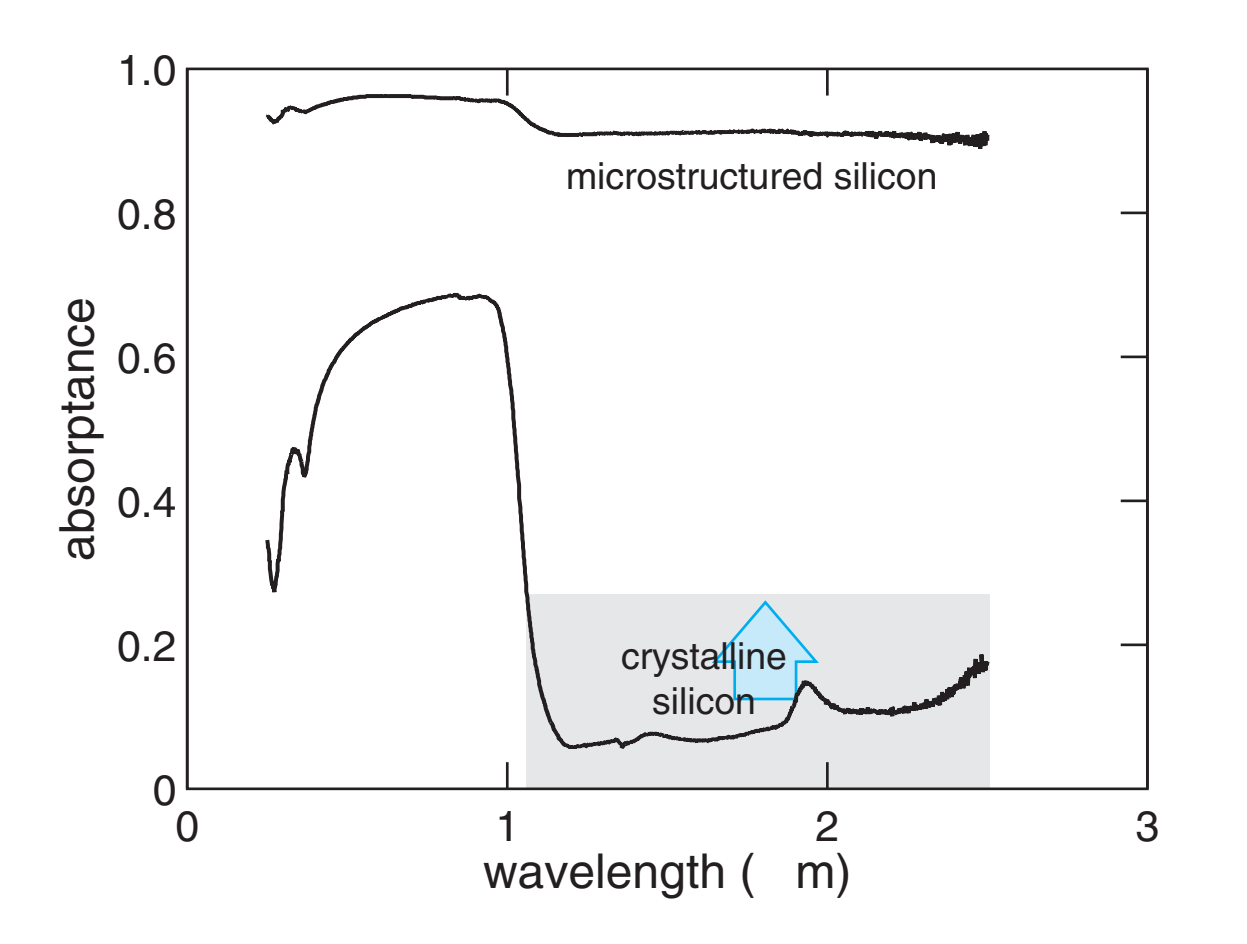
Introduction

multiple reflections enhance absorption



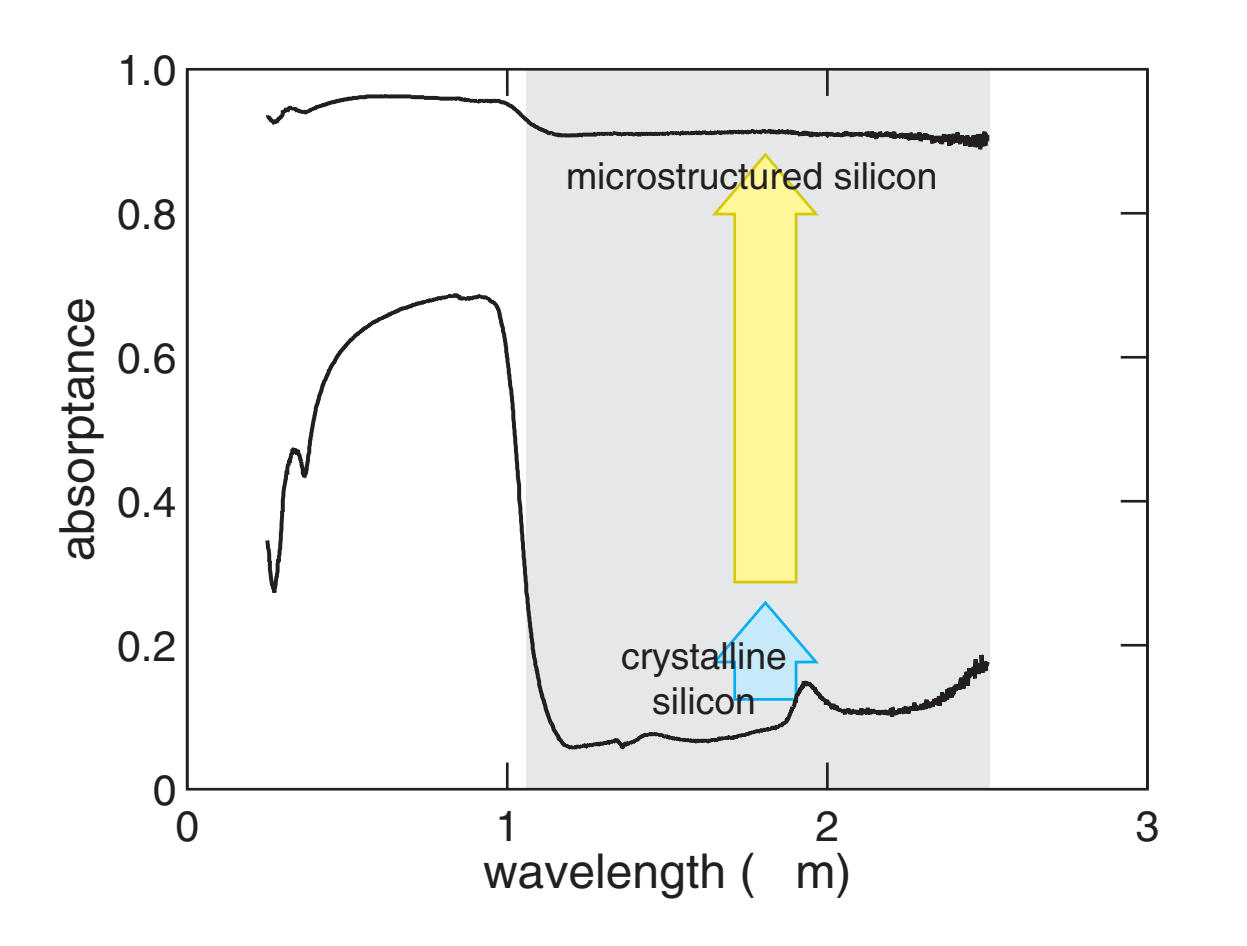
Introduction

multiple reflections enhance absorption



Introduction

electronic band structure changes



Introduction

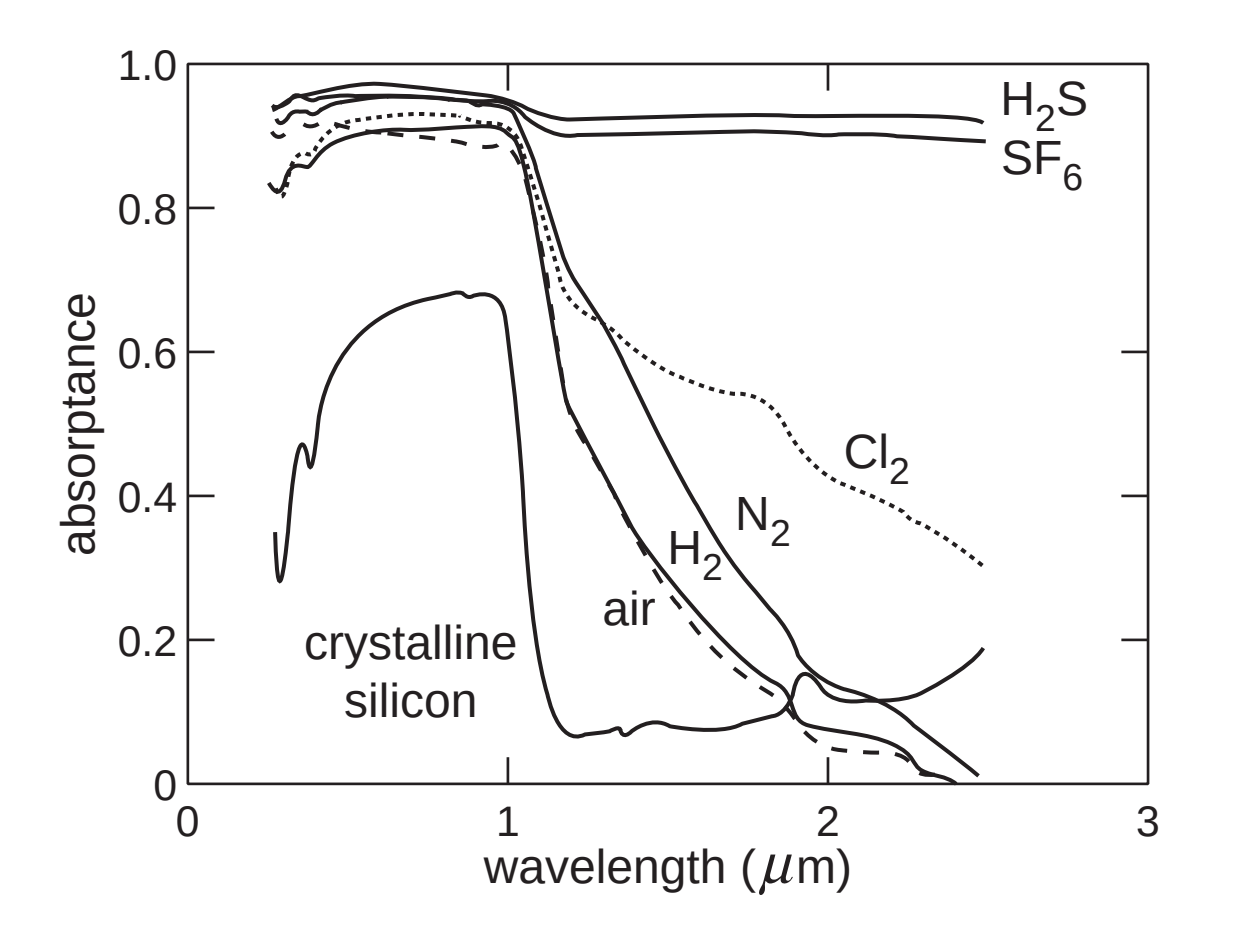
band structure changes: defects and/or impurities

Outline

- optical hyperdoping
- photoelectron generation
- photoconductive gain

Optical hyperdoping

microstructure with different gases

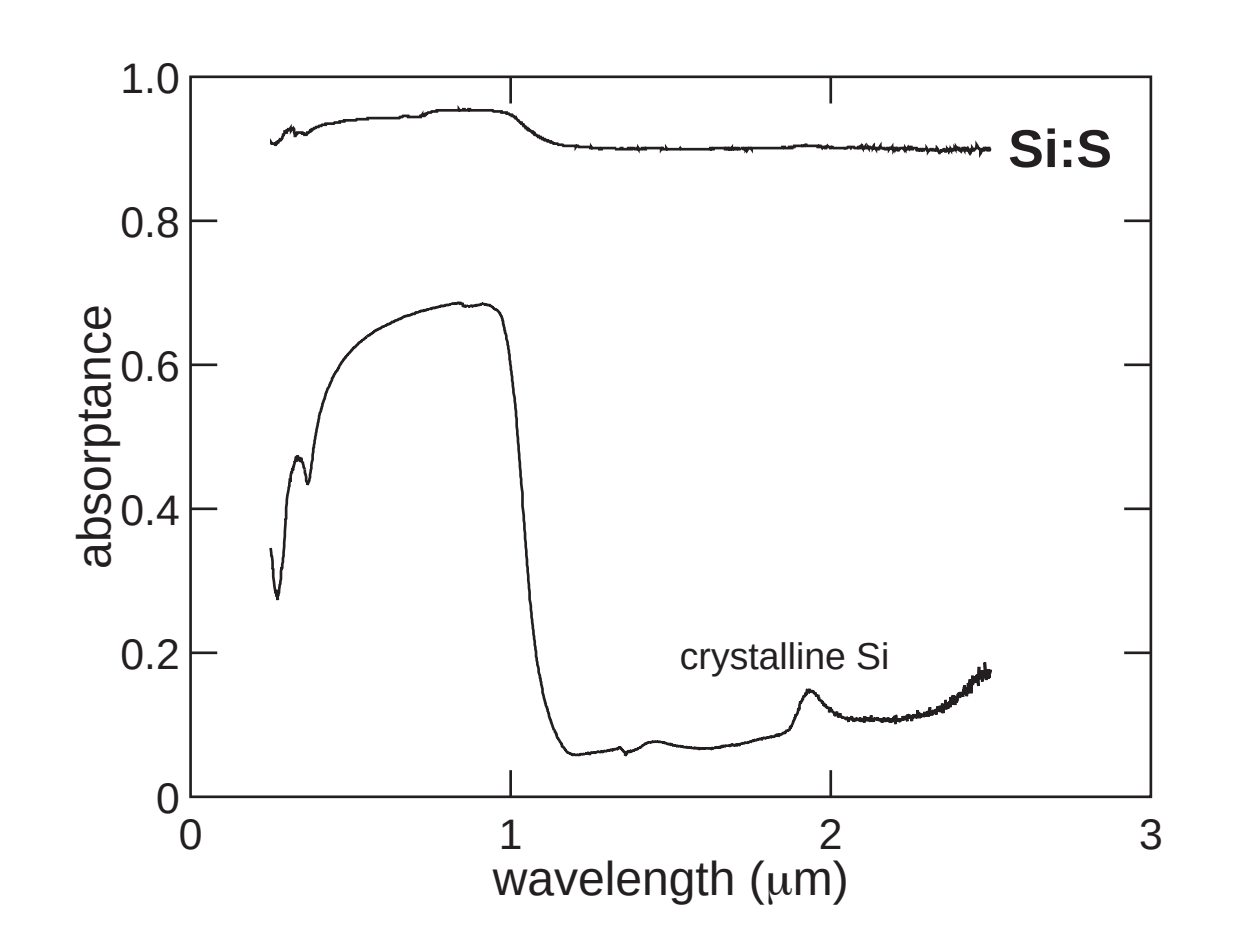


Introduction

sulfur required for below band gap absorption

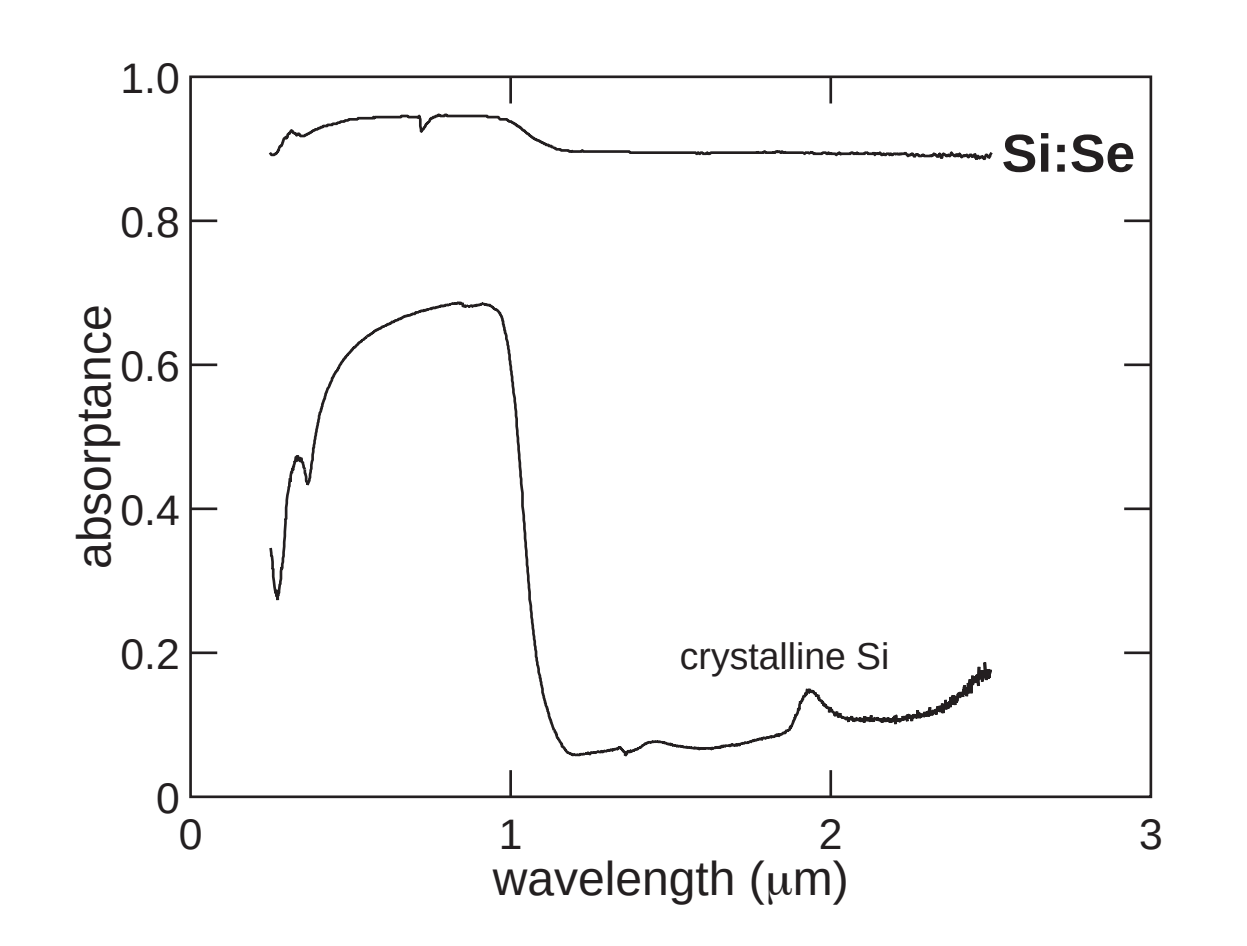
Optical hyperdoping

other chalcogens yield similar results



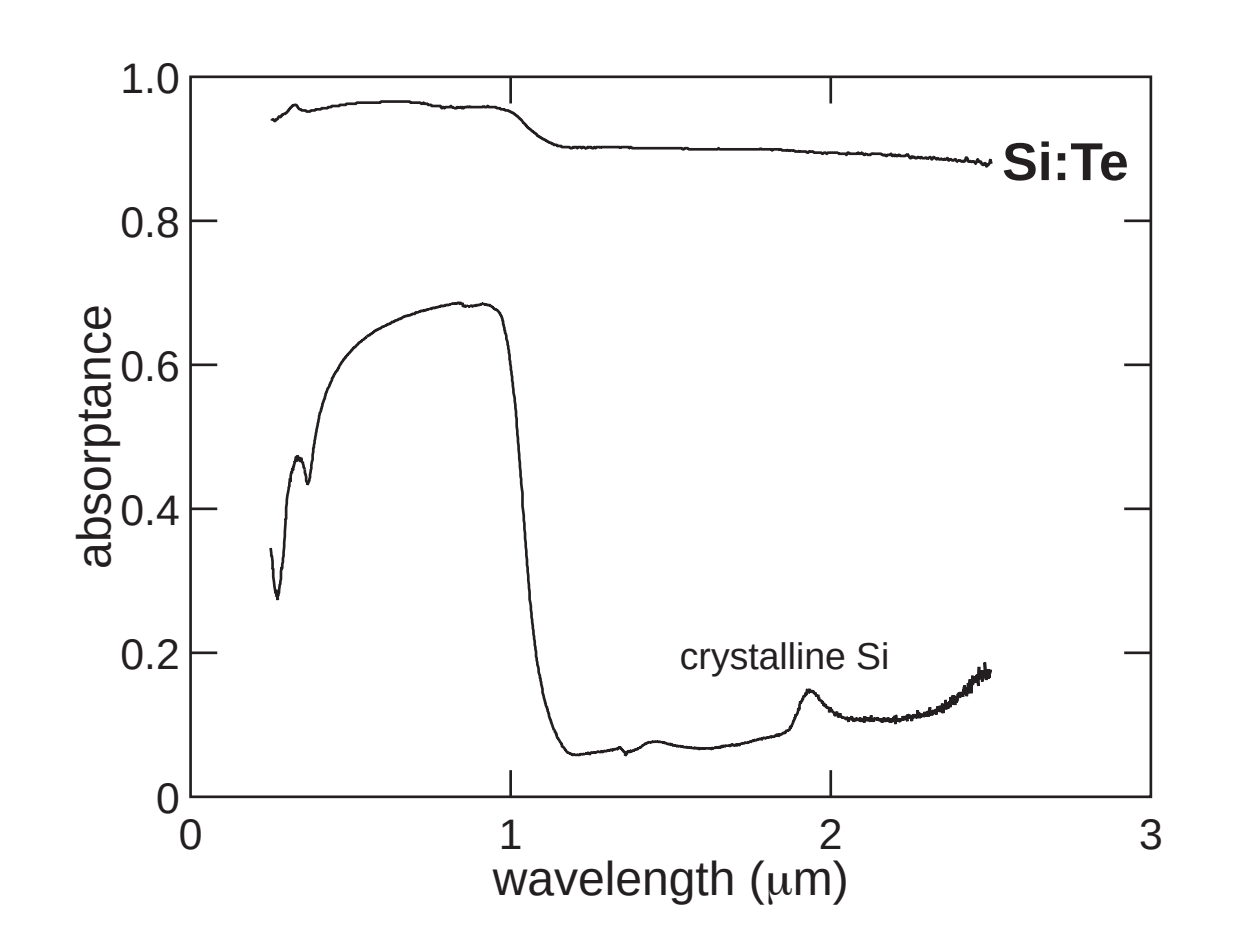
Optical hyperdoping

other chalcogens yield similar results

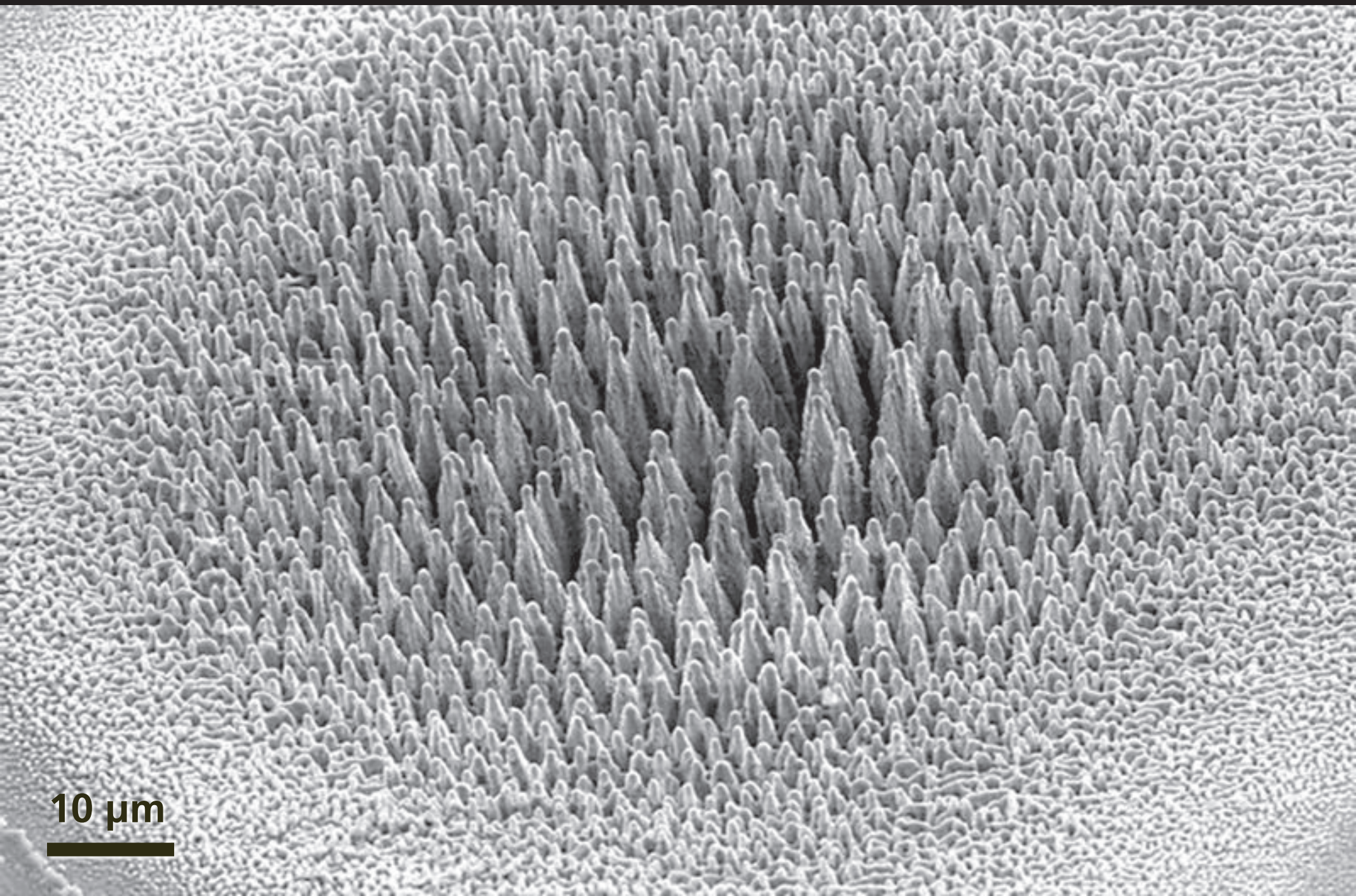


Optical hyperdoping

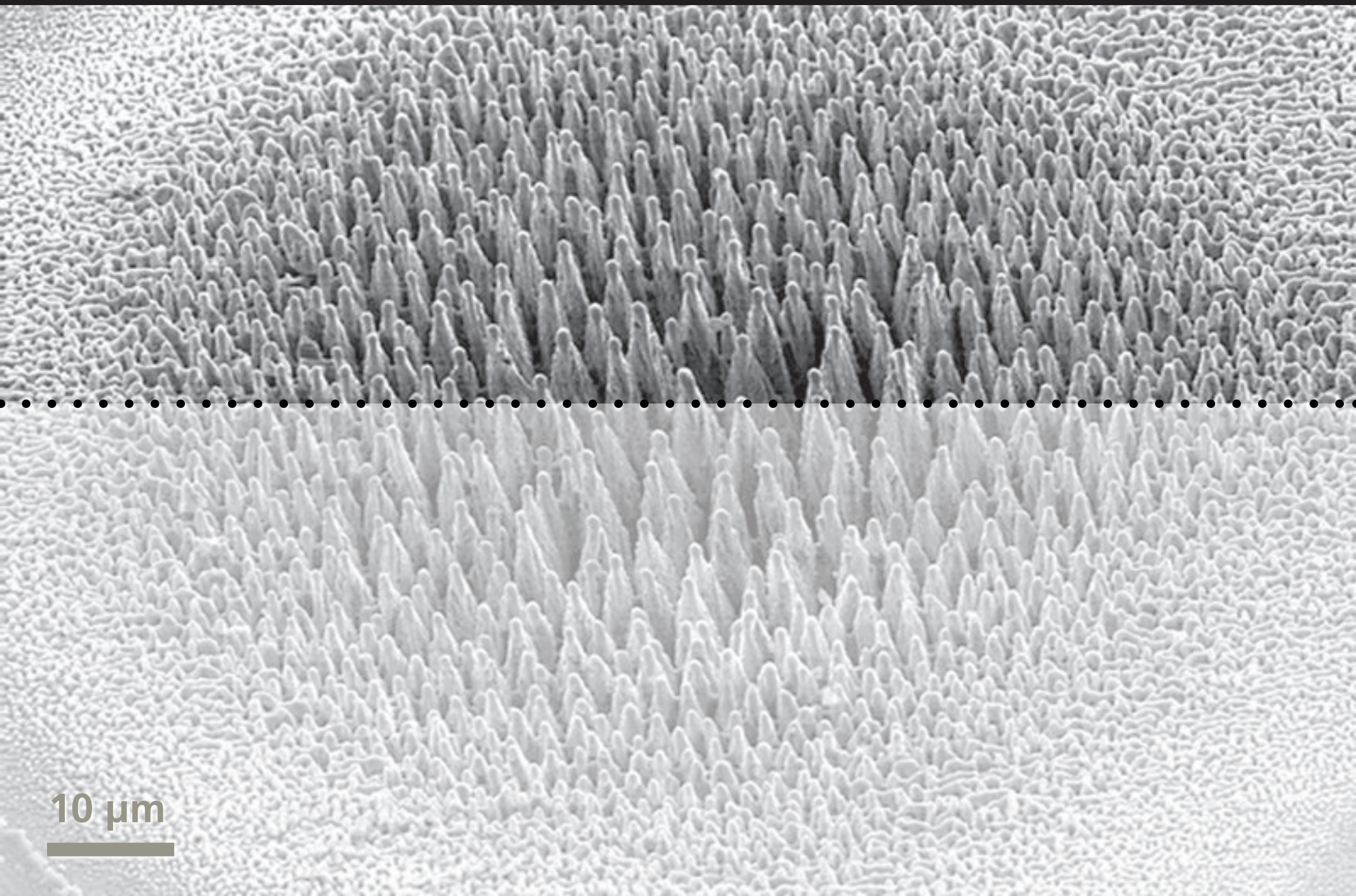
other chalcogens yield similar results



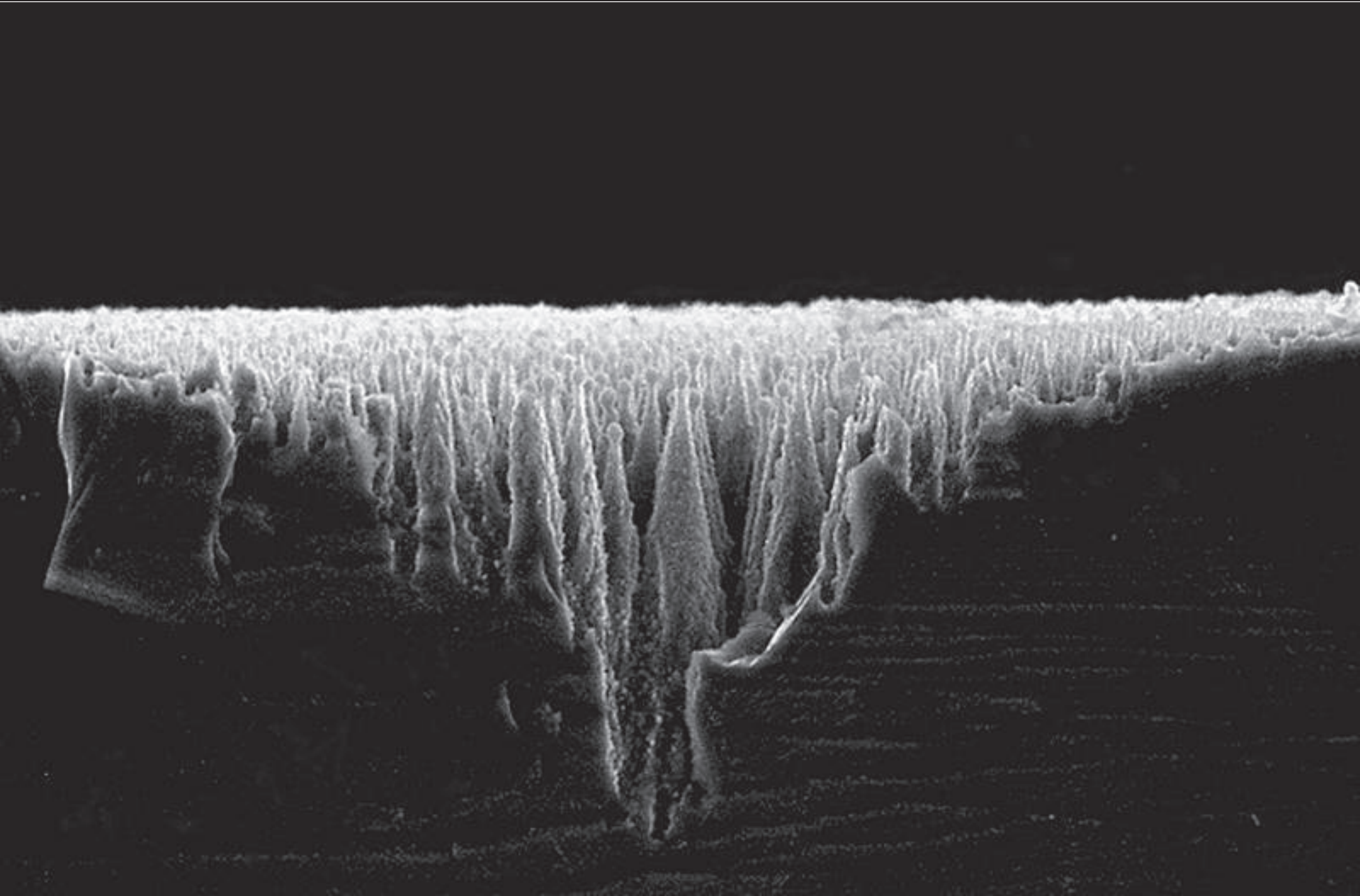
Optical hyperdoping



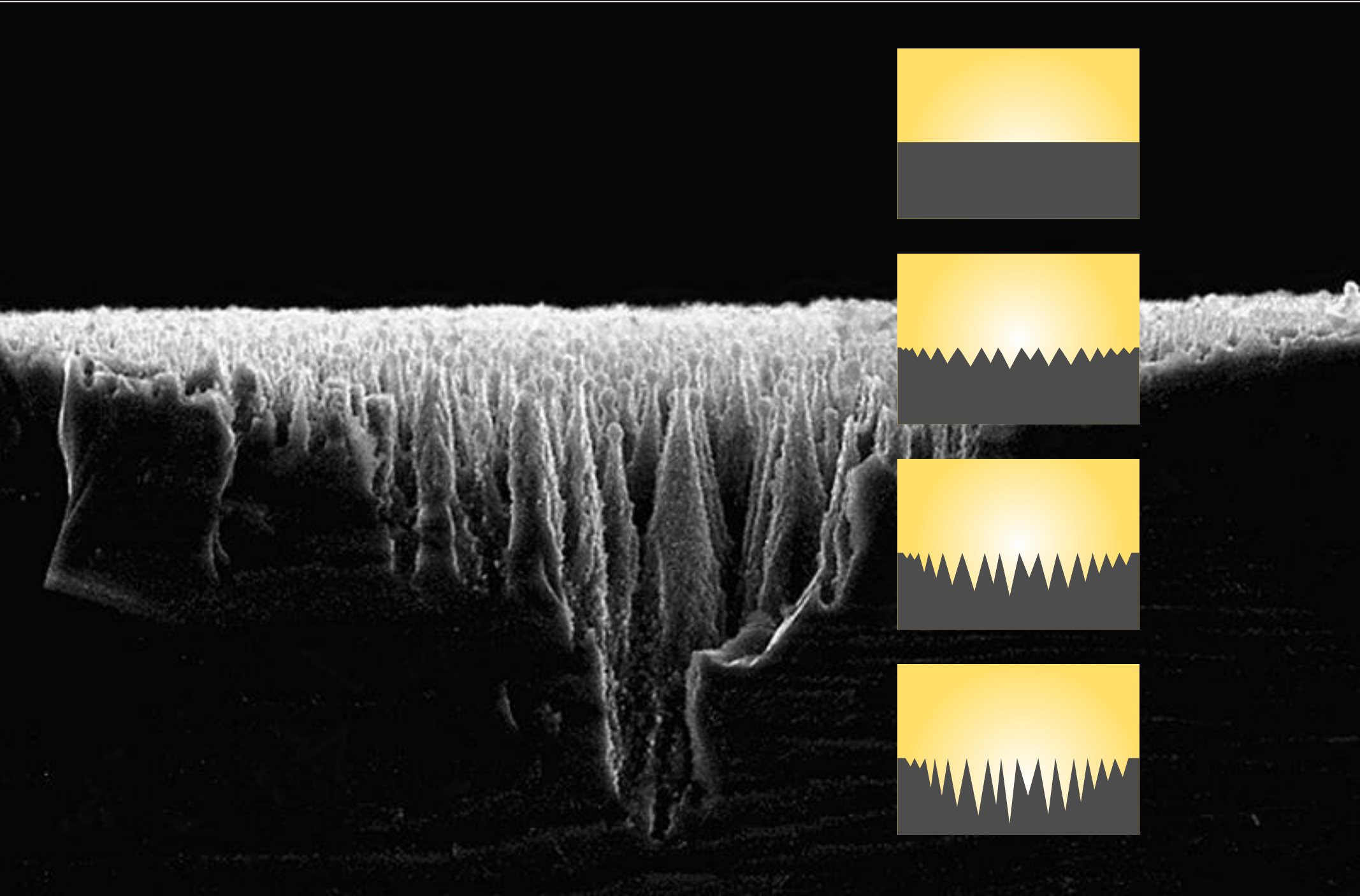
Optical hyperdoping



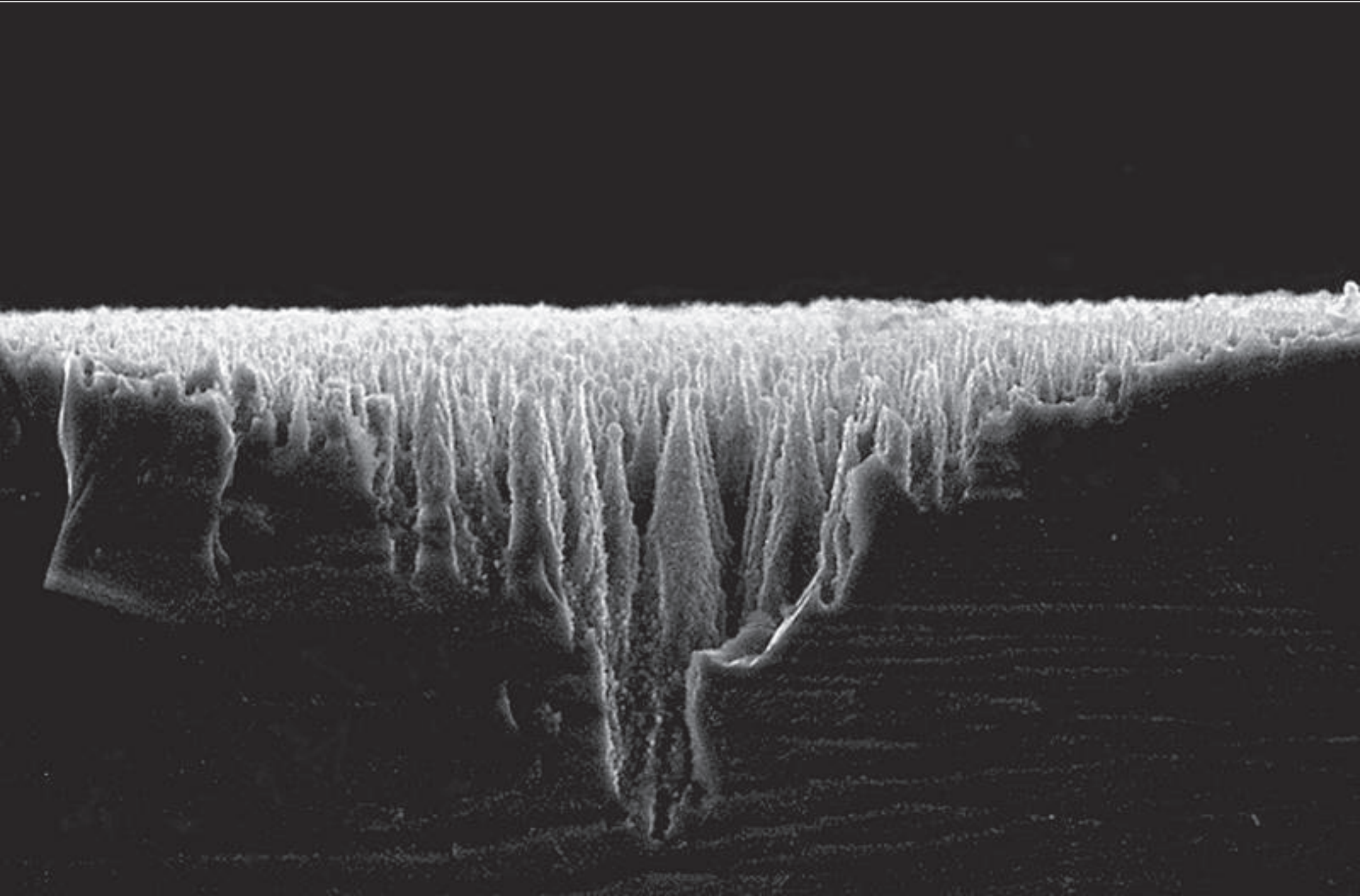
Optical hyperdoping



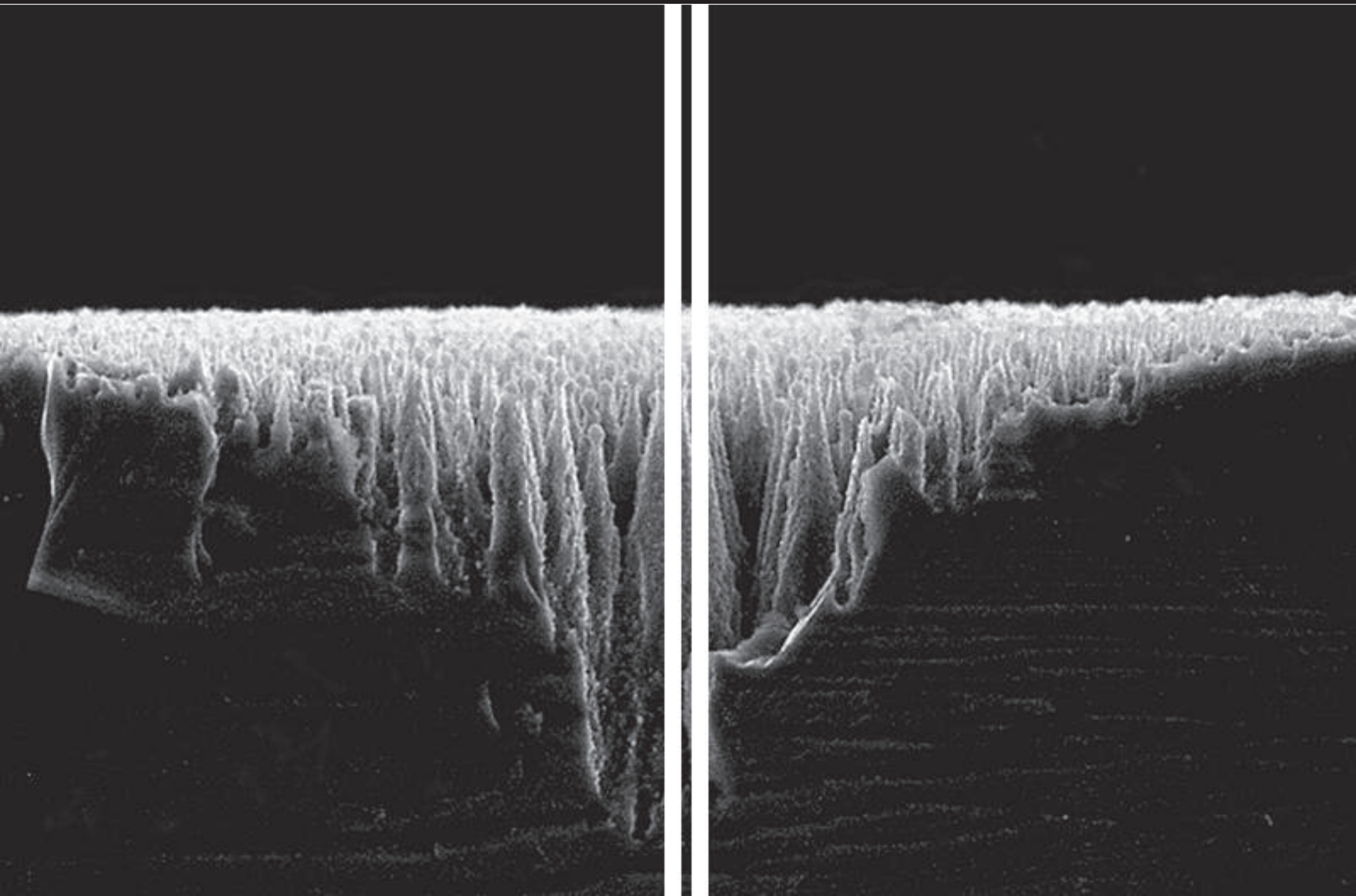
Optical hyperdoping



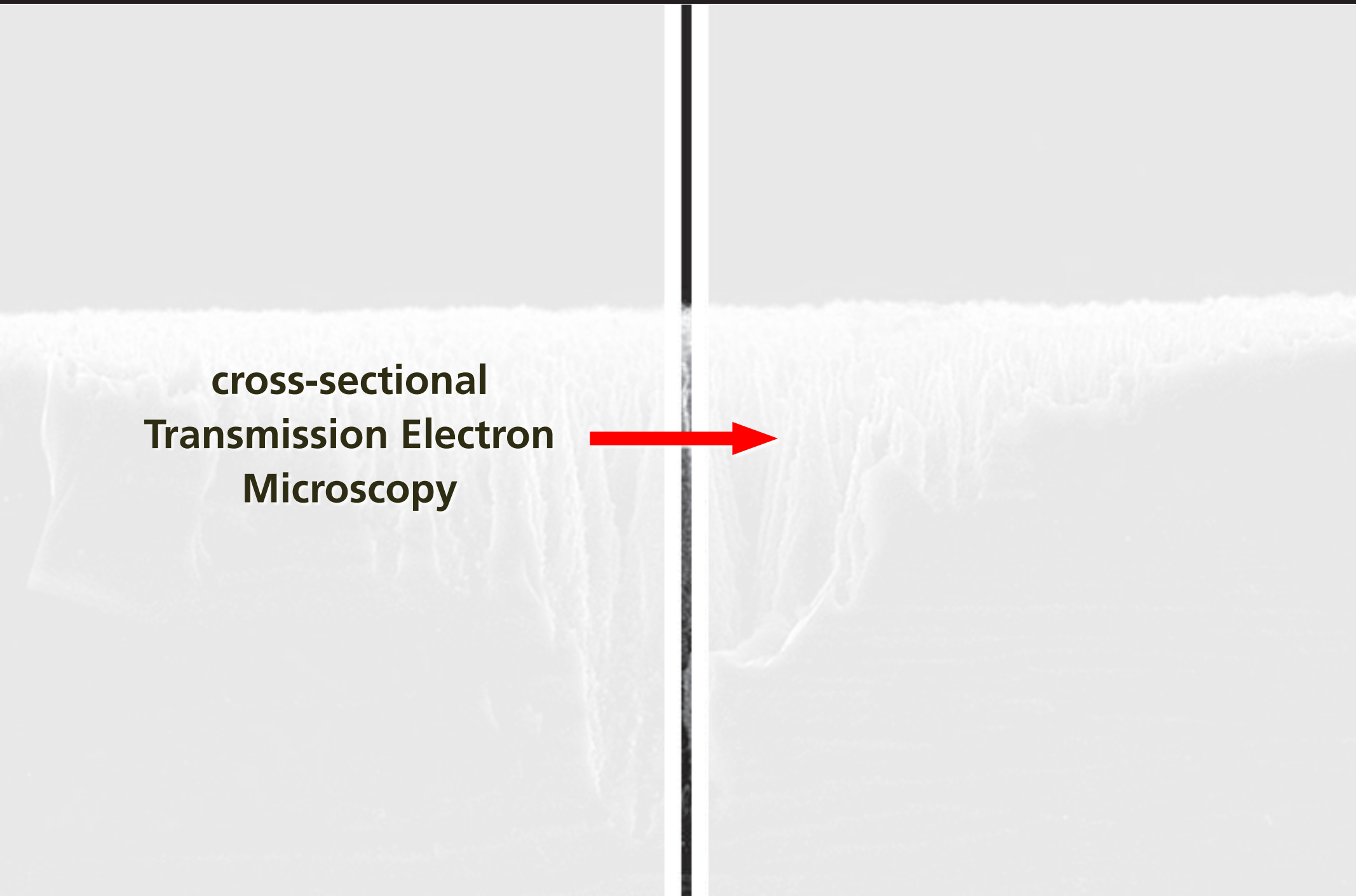
Optical hyperdoping



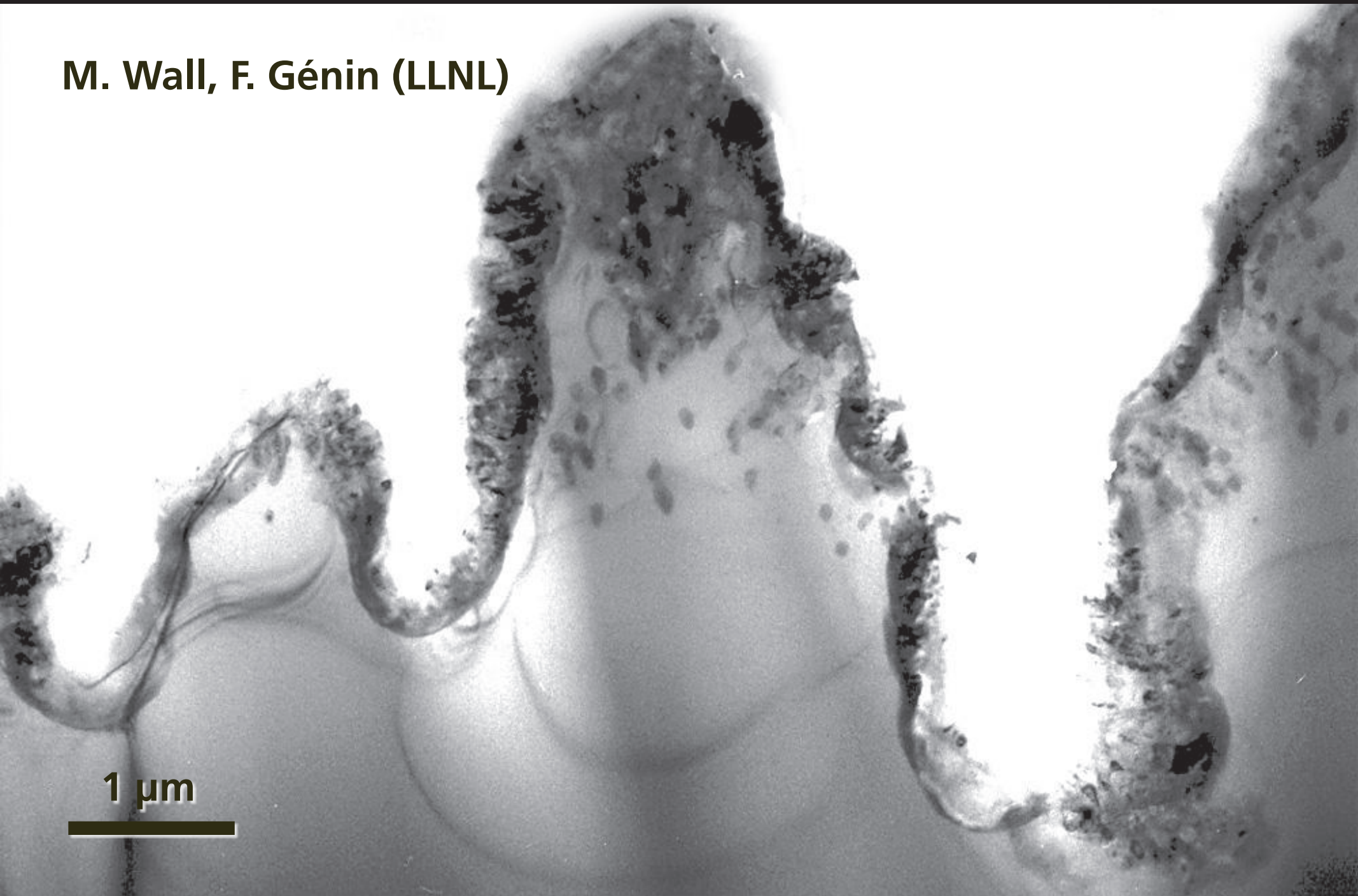
Optical hyperdoping



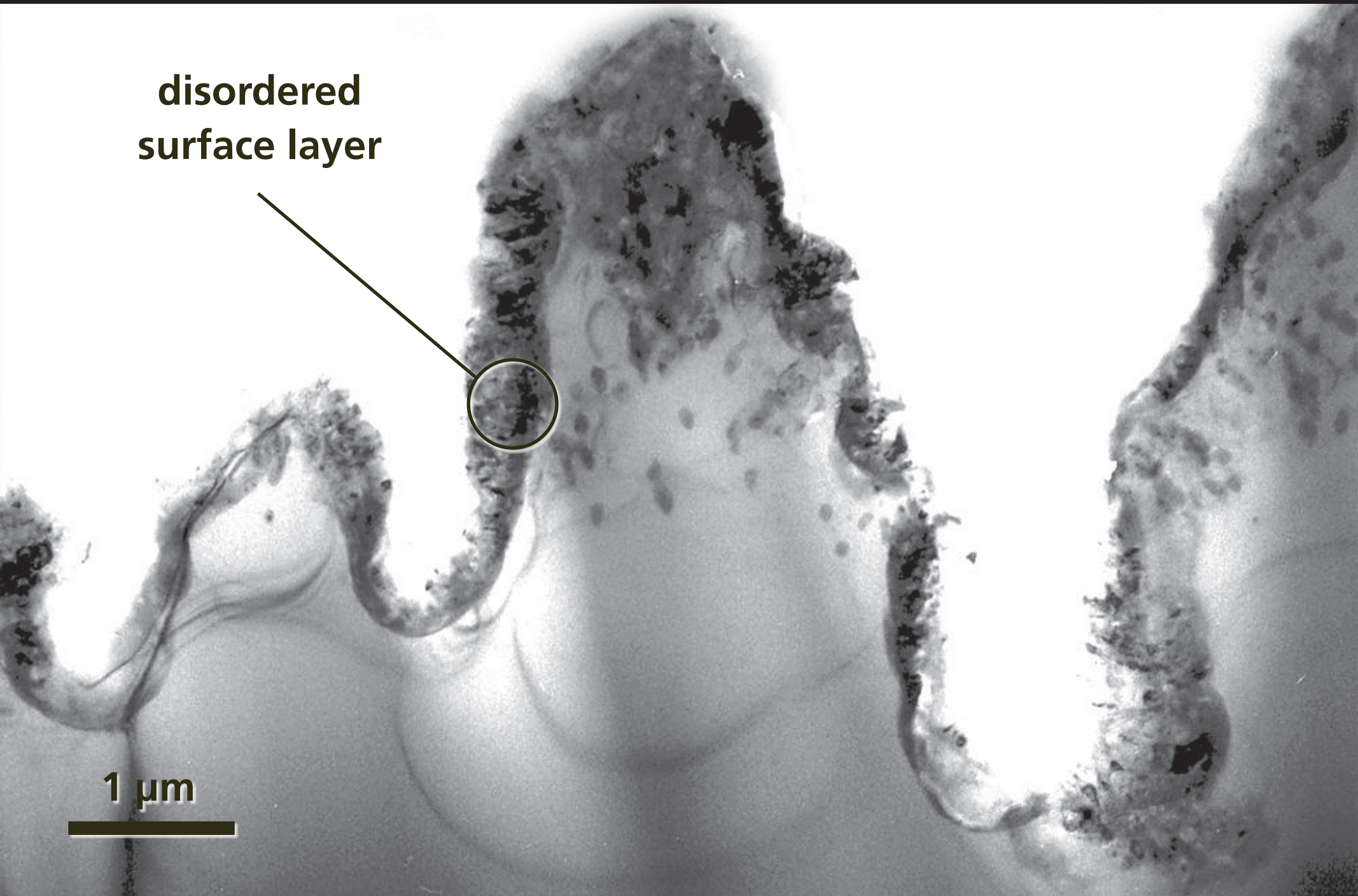
Optical hyperdoping



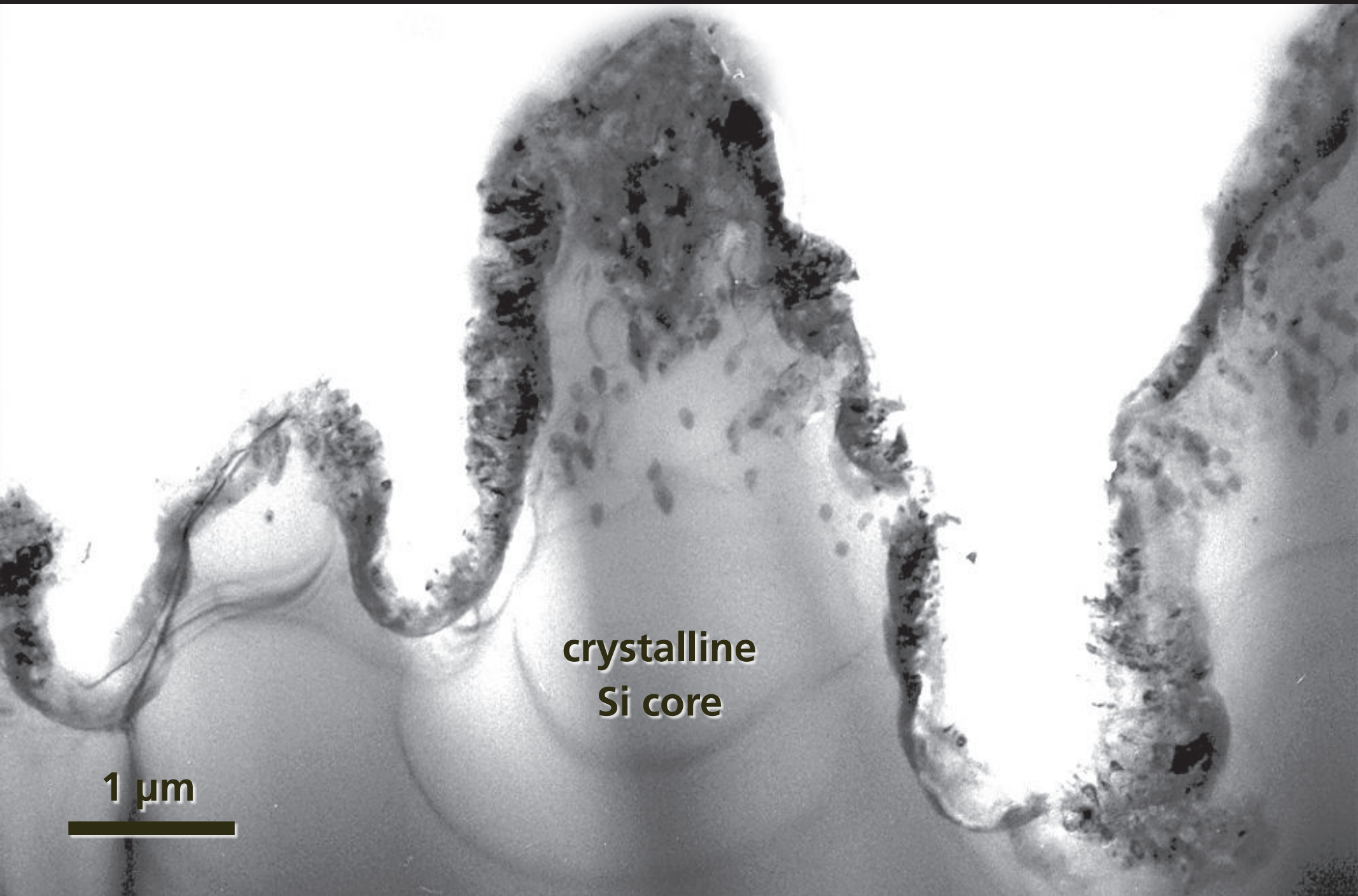
Optical hyperdoping



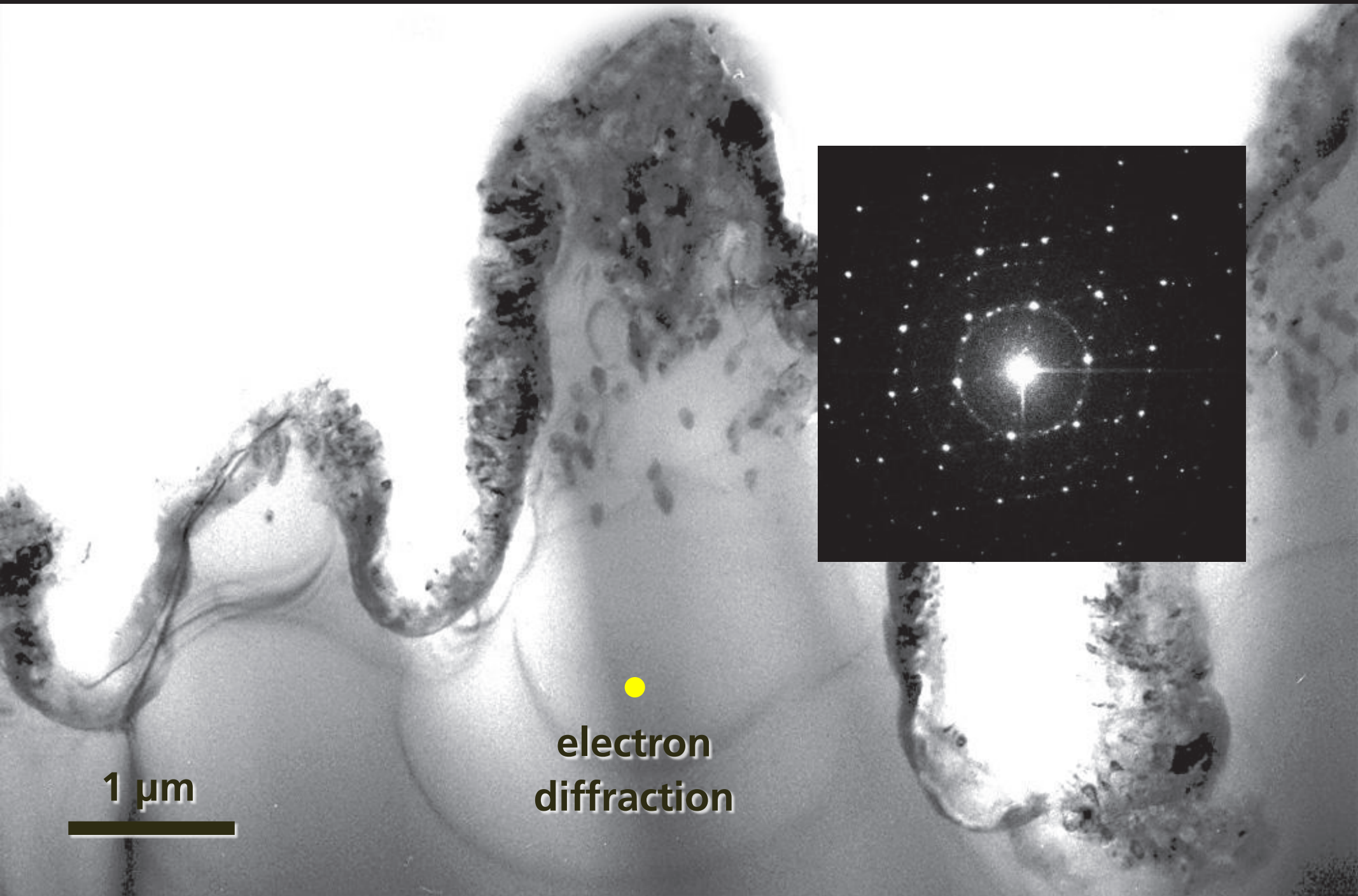
Optical hyperdoping



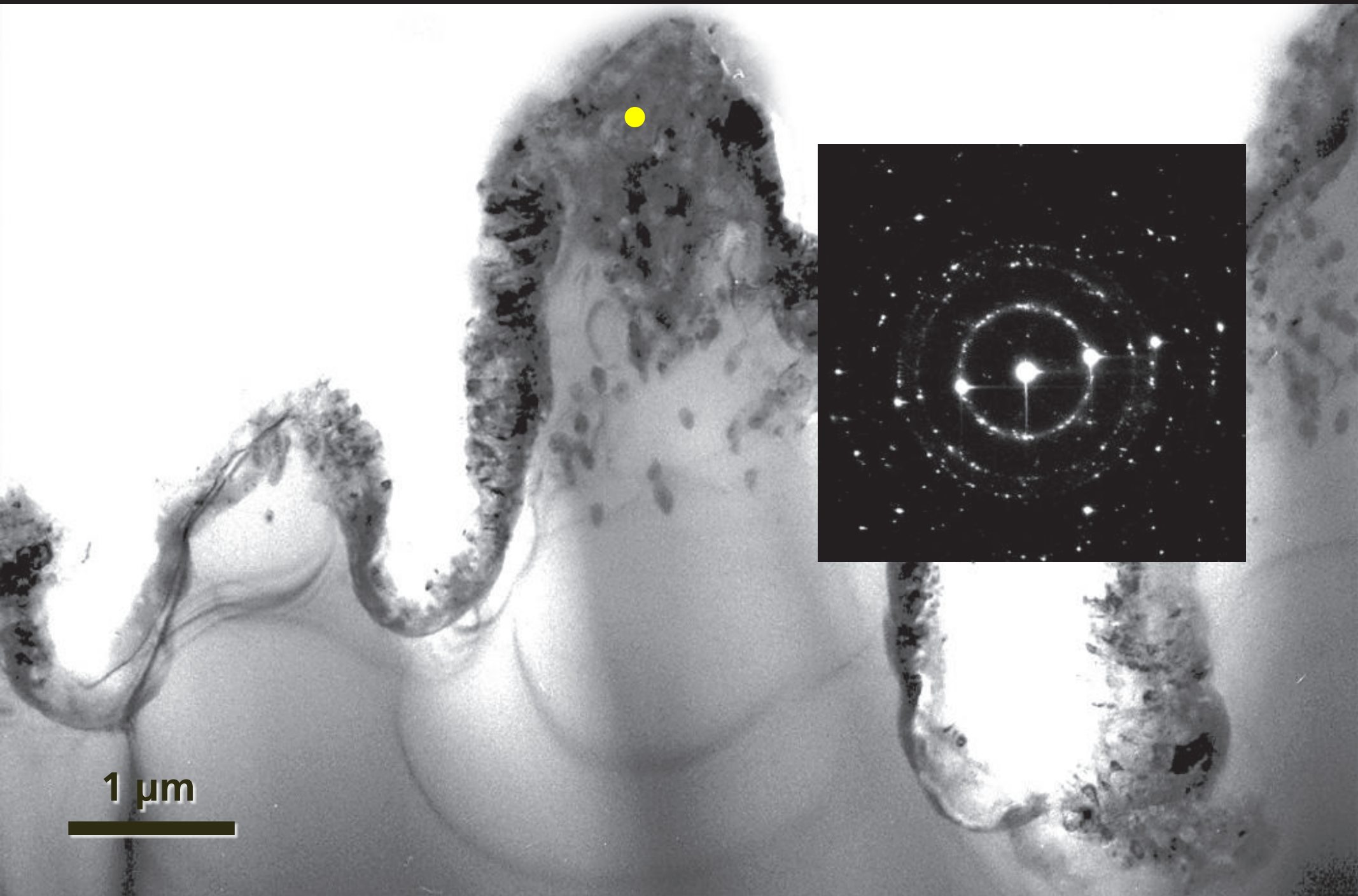
Optical hyperdoping



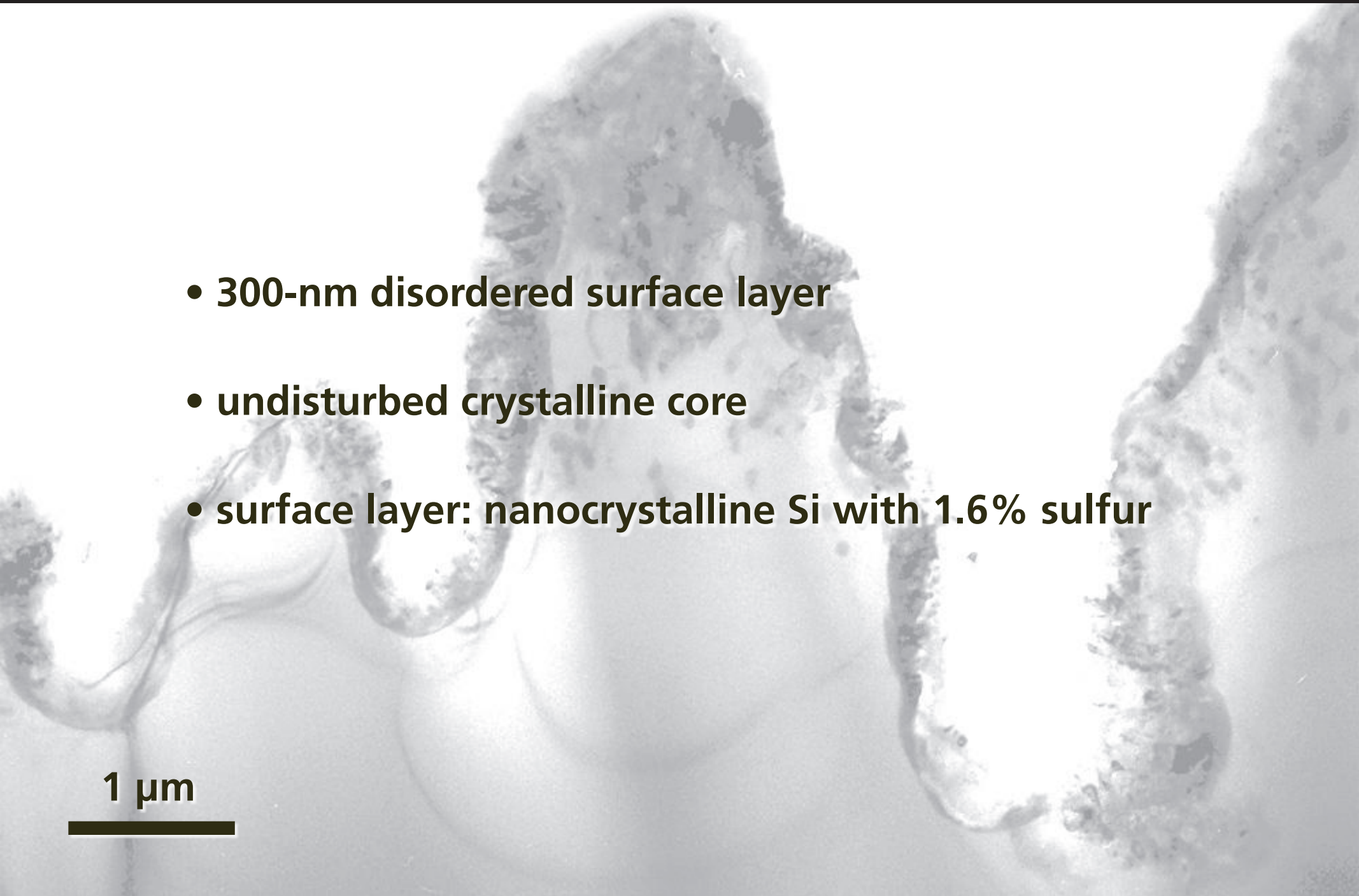
Optical hyperdoping



Optical hyperdoping



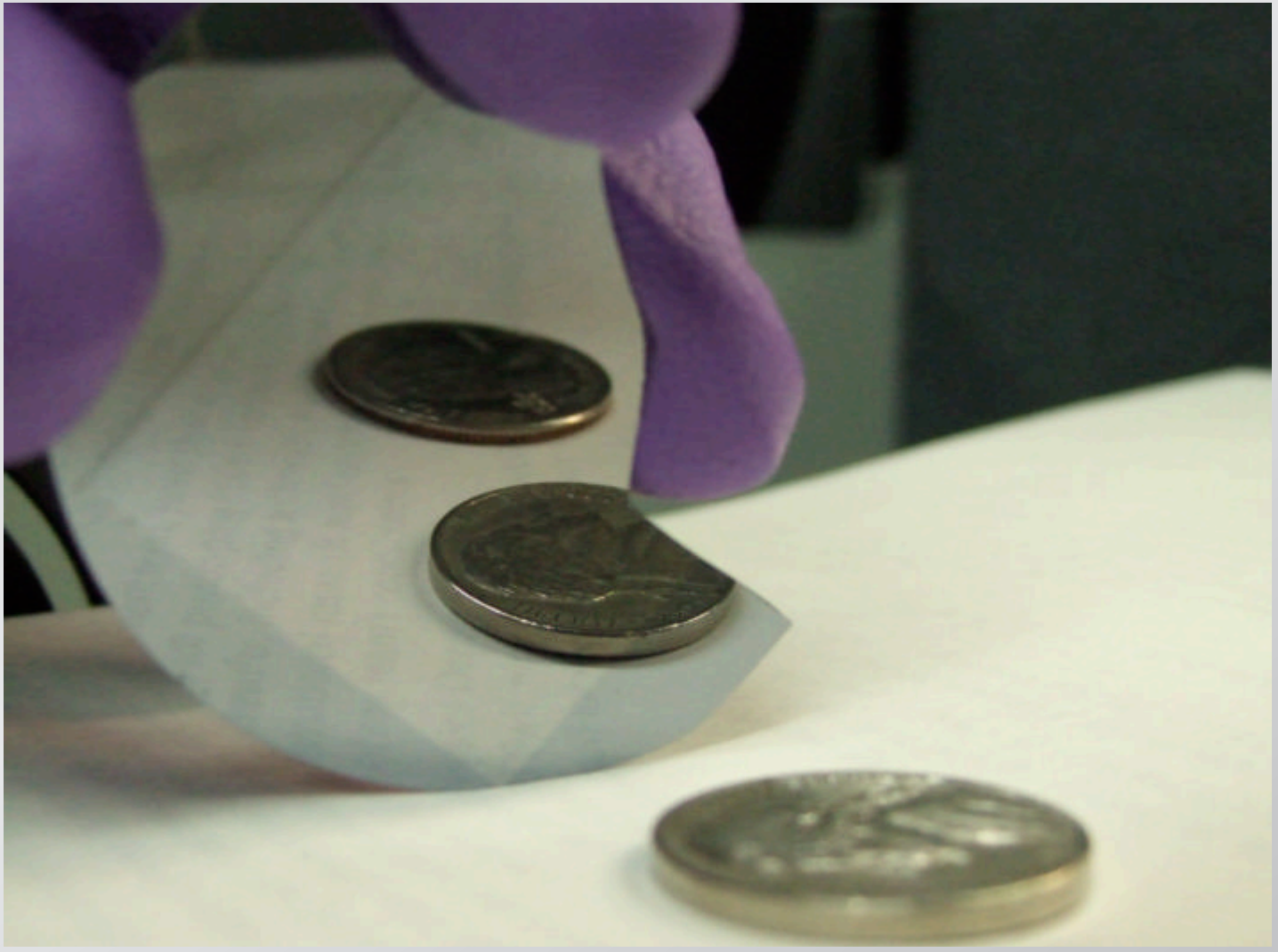
Optical hyperdoping



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

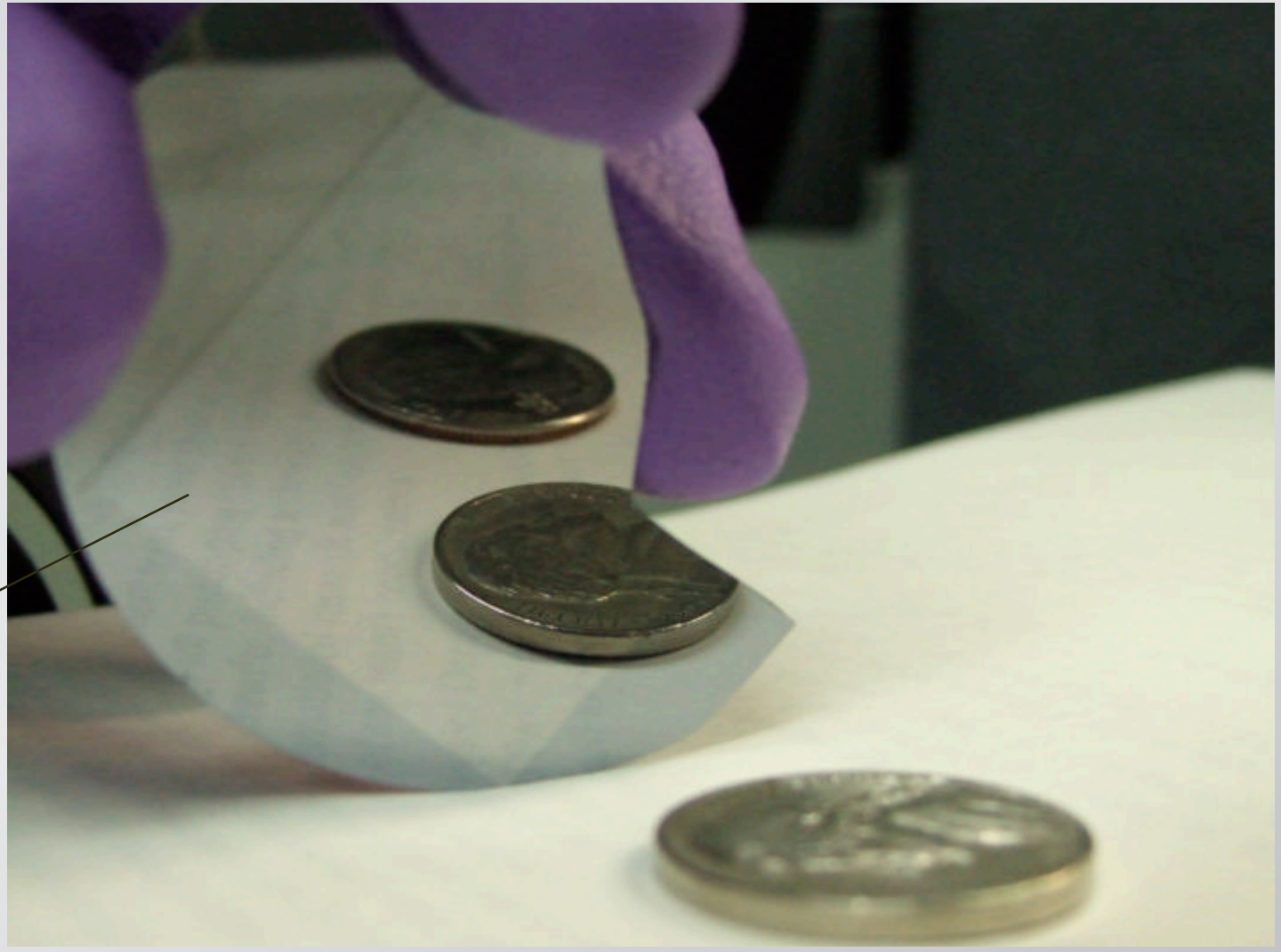
Optical hyperdoping

decouple ablation from melting



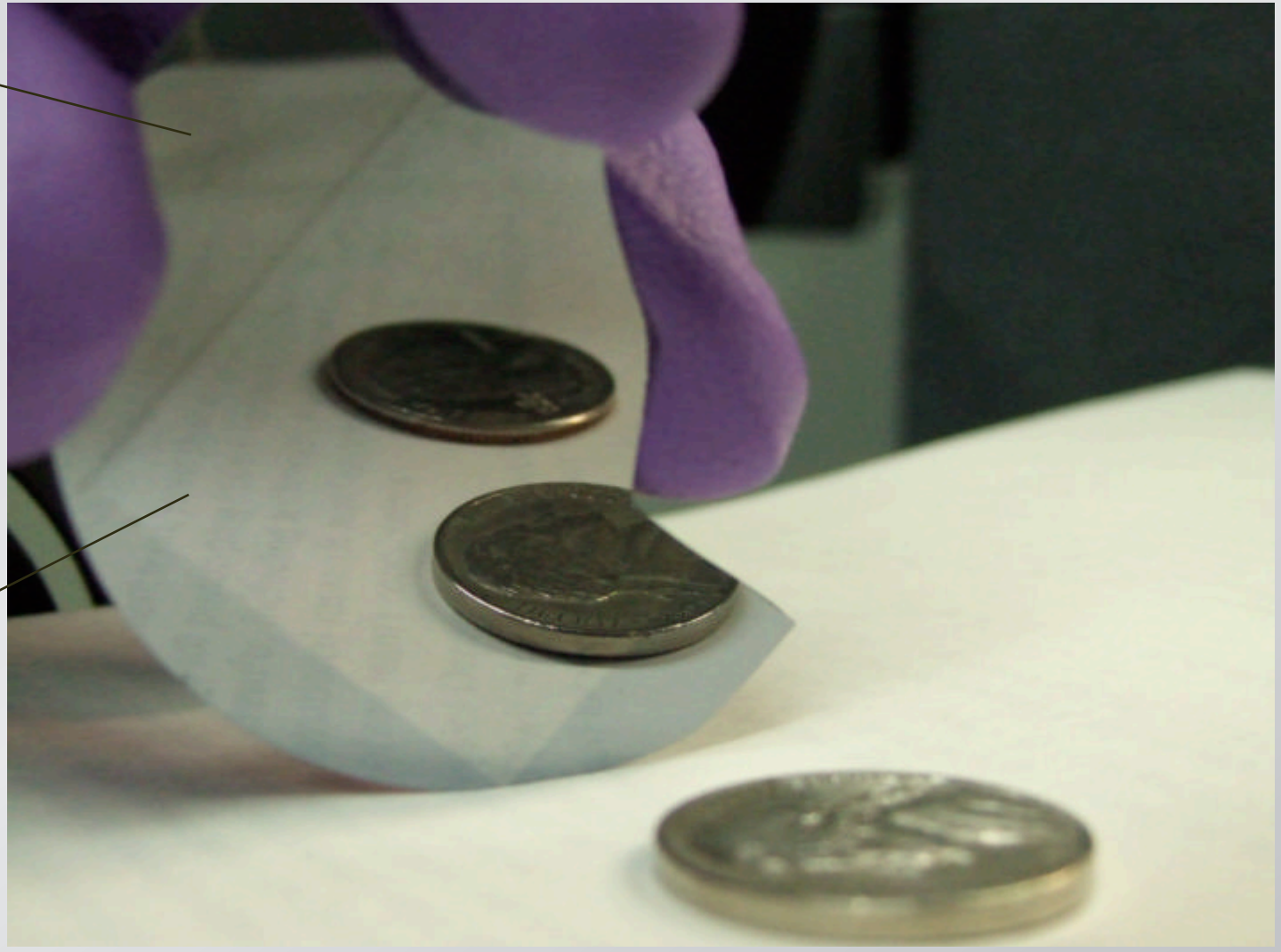
Optical hyperdoping

decouple ablation from melting



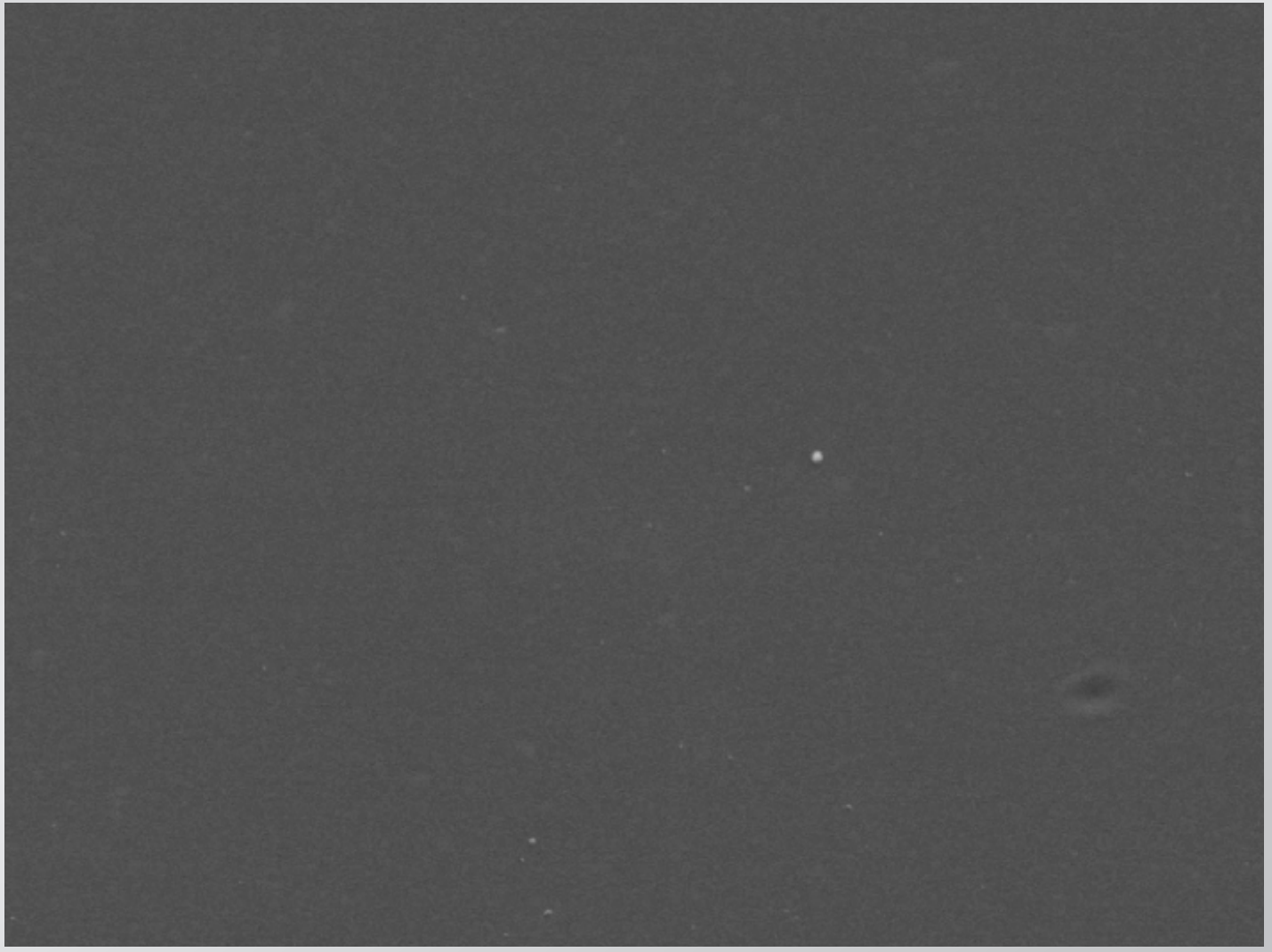
Optical hyperdoping

decouple ablation from melting



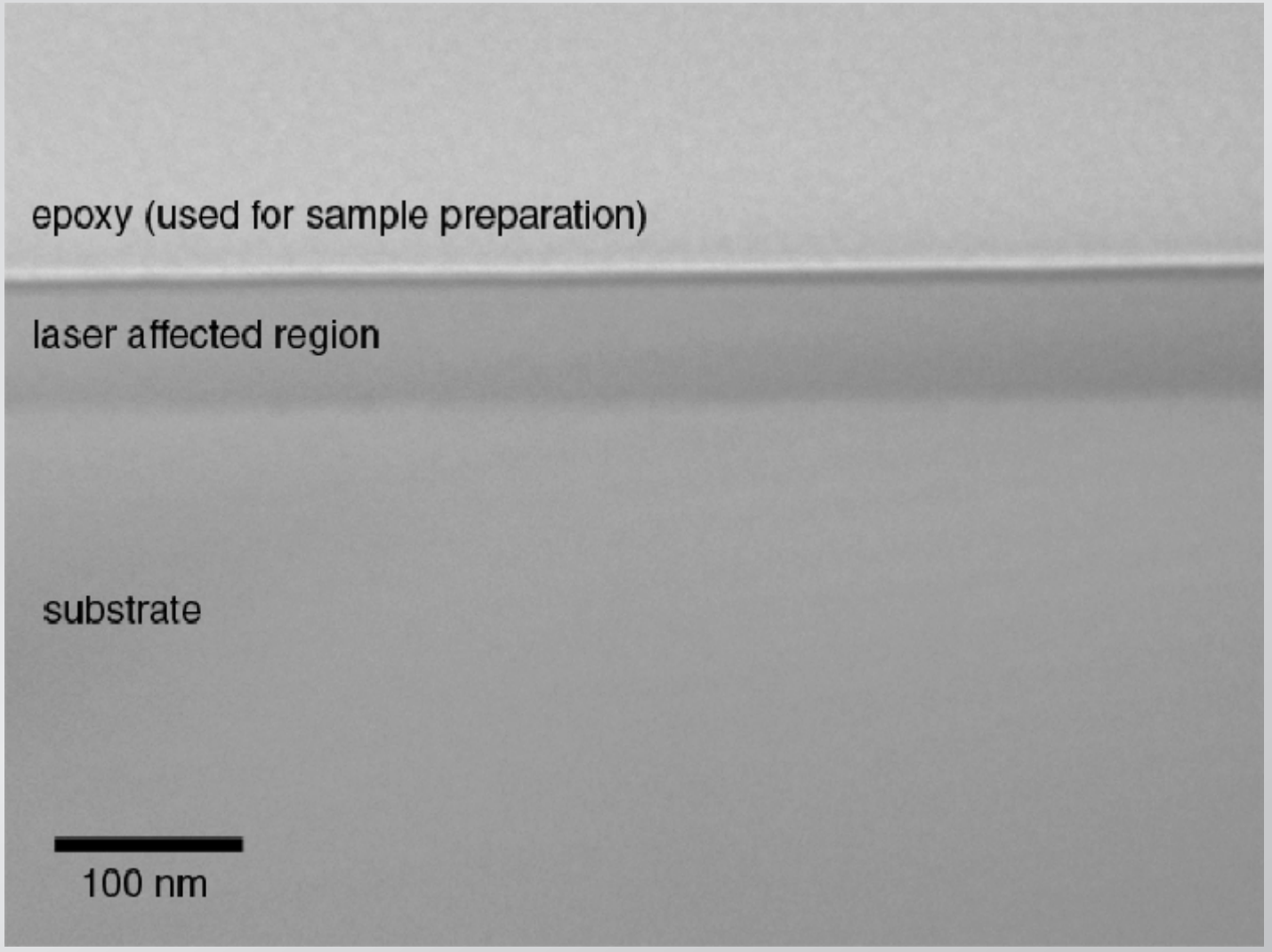
Optical hyperdoping

decouple ablation from melting



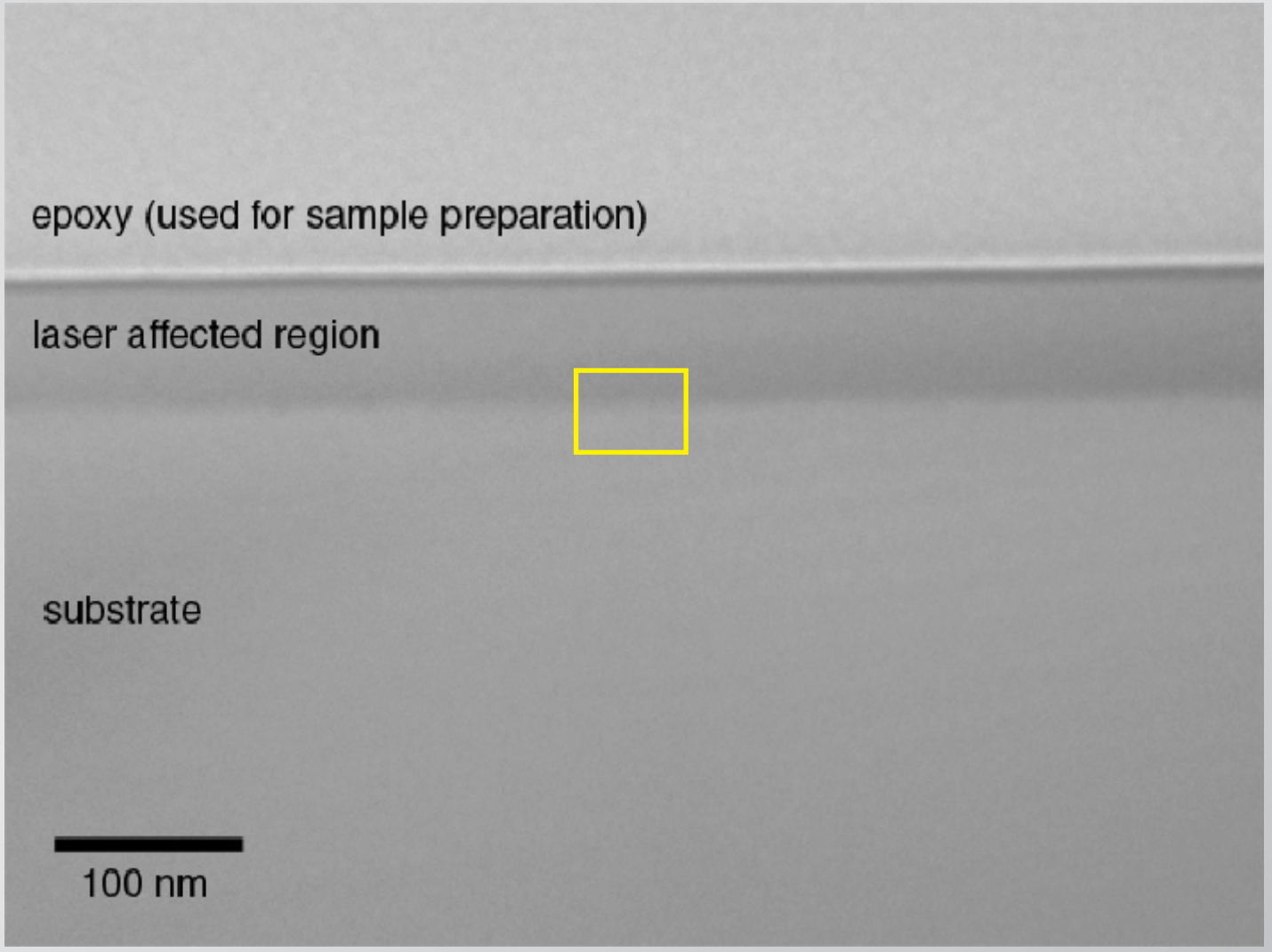
Optical hyperdoping

decouple ablation from melting



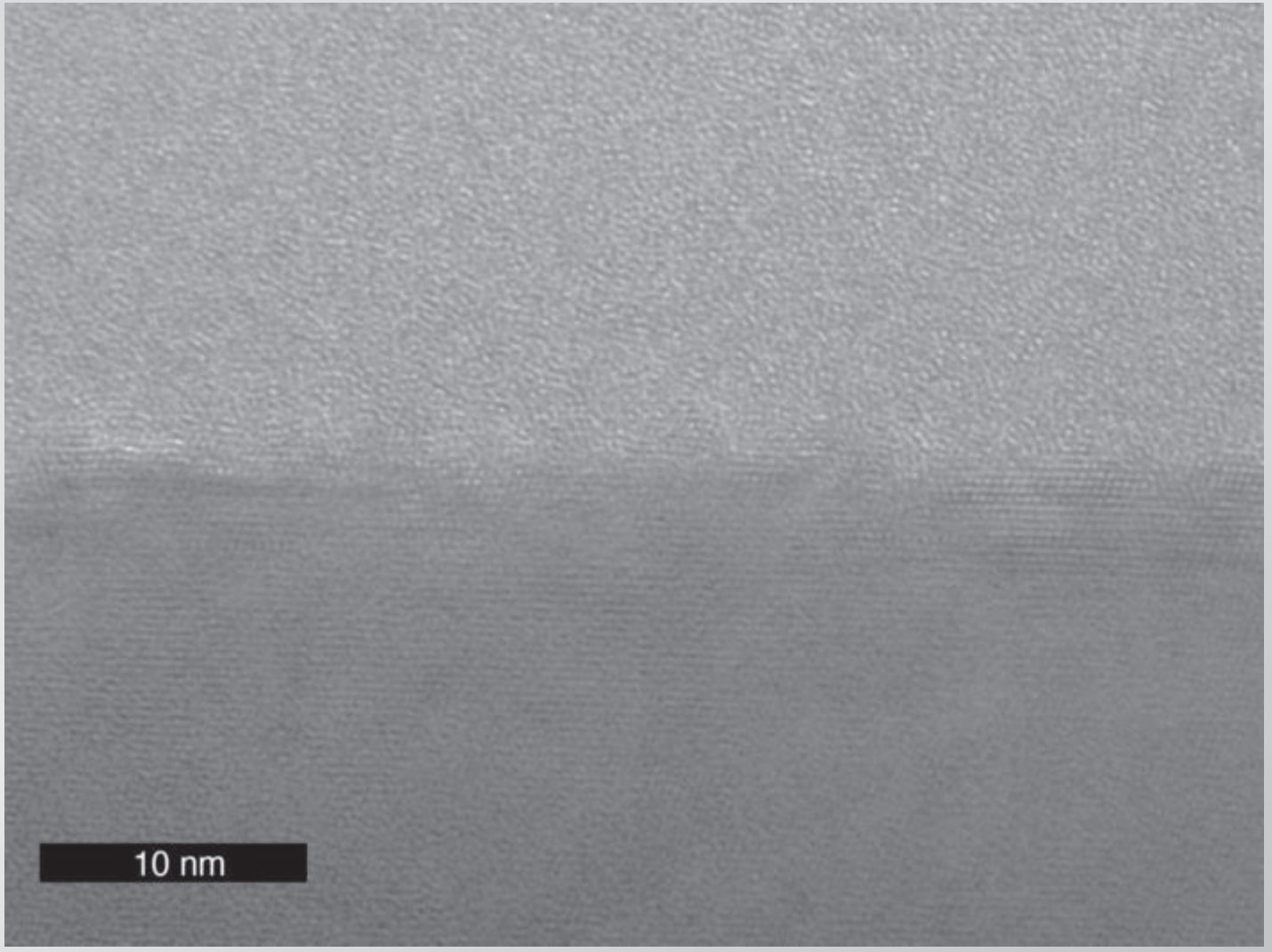
Optical hyperdoping

decouple ablation from melting



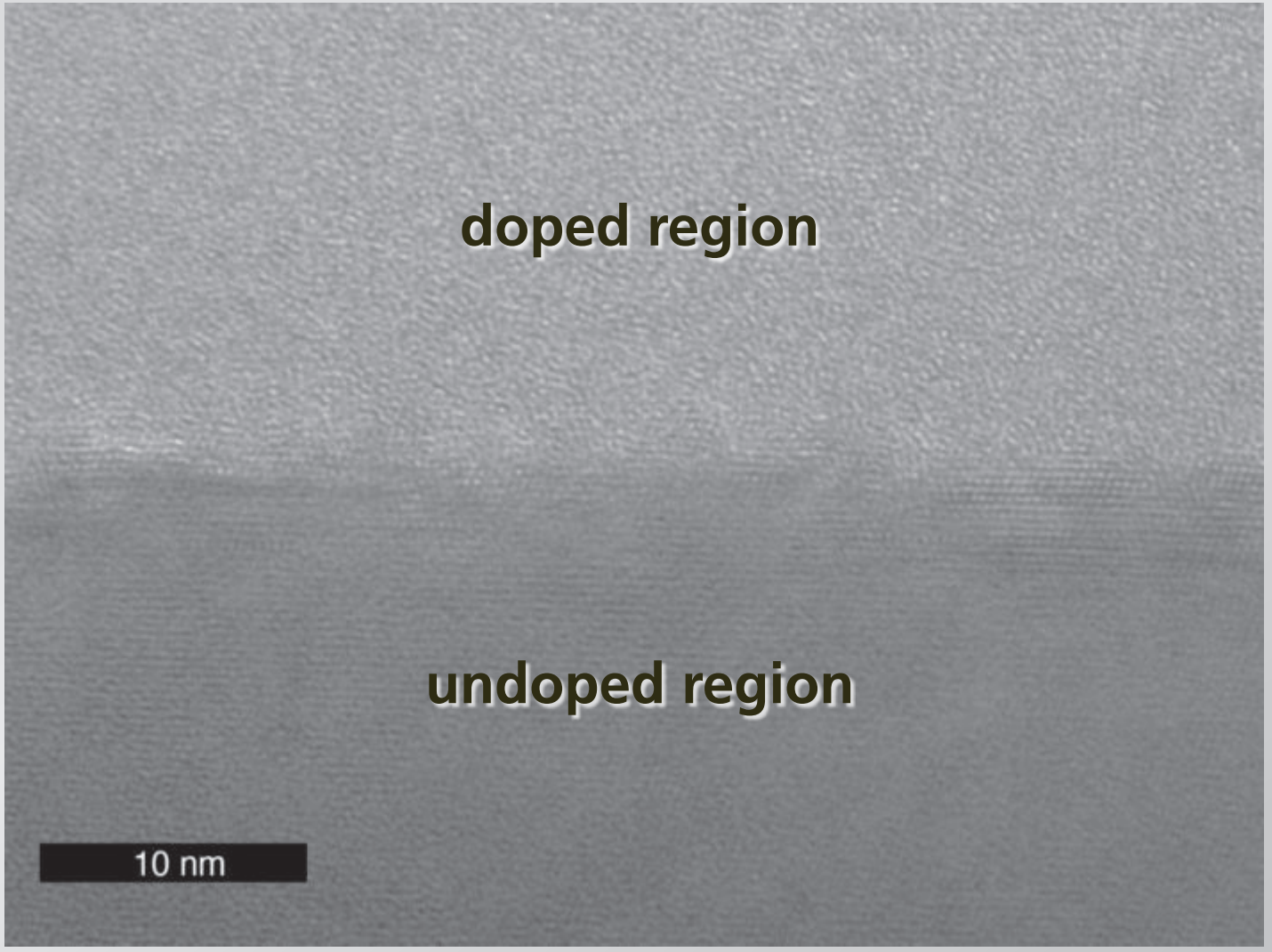
Optical hyperdoping

decouple ablation from melting



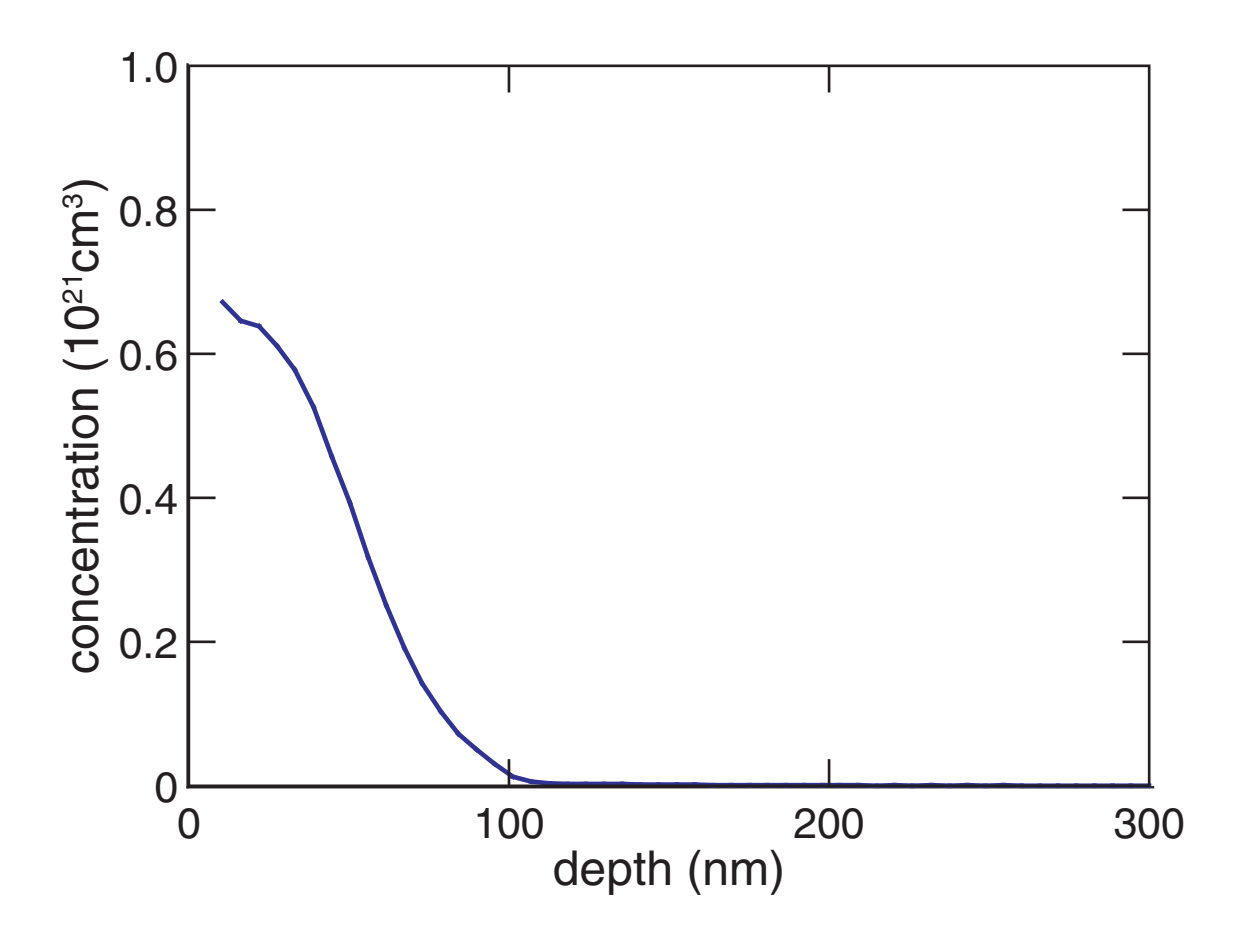
Optical hyperdoping

decouple ablation from melting

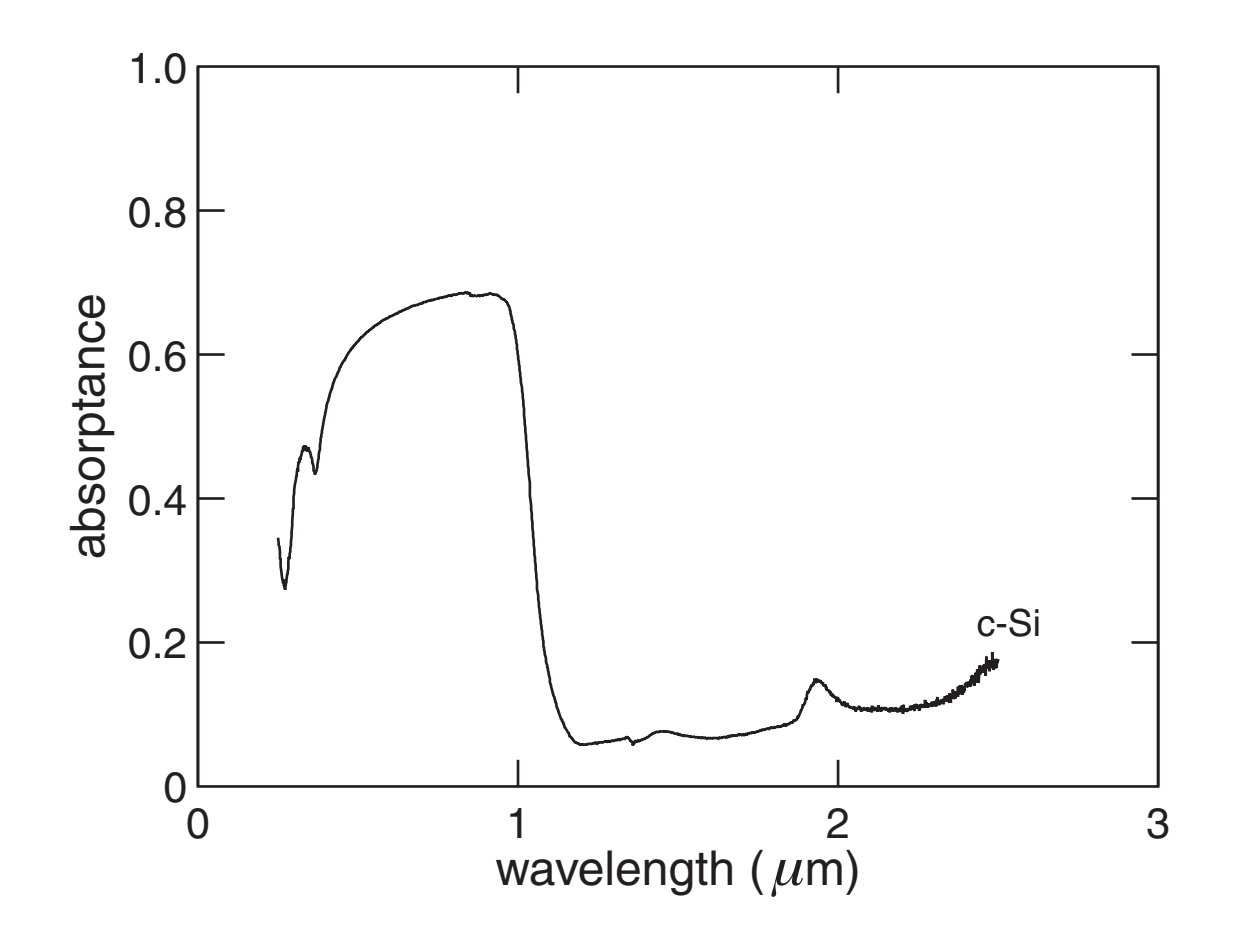


Optical hyperdoping

secondary ion mass spectrometry

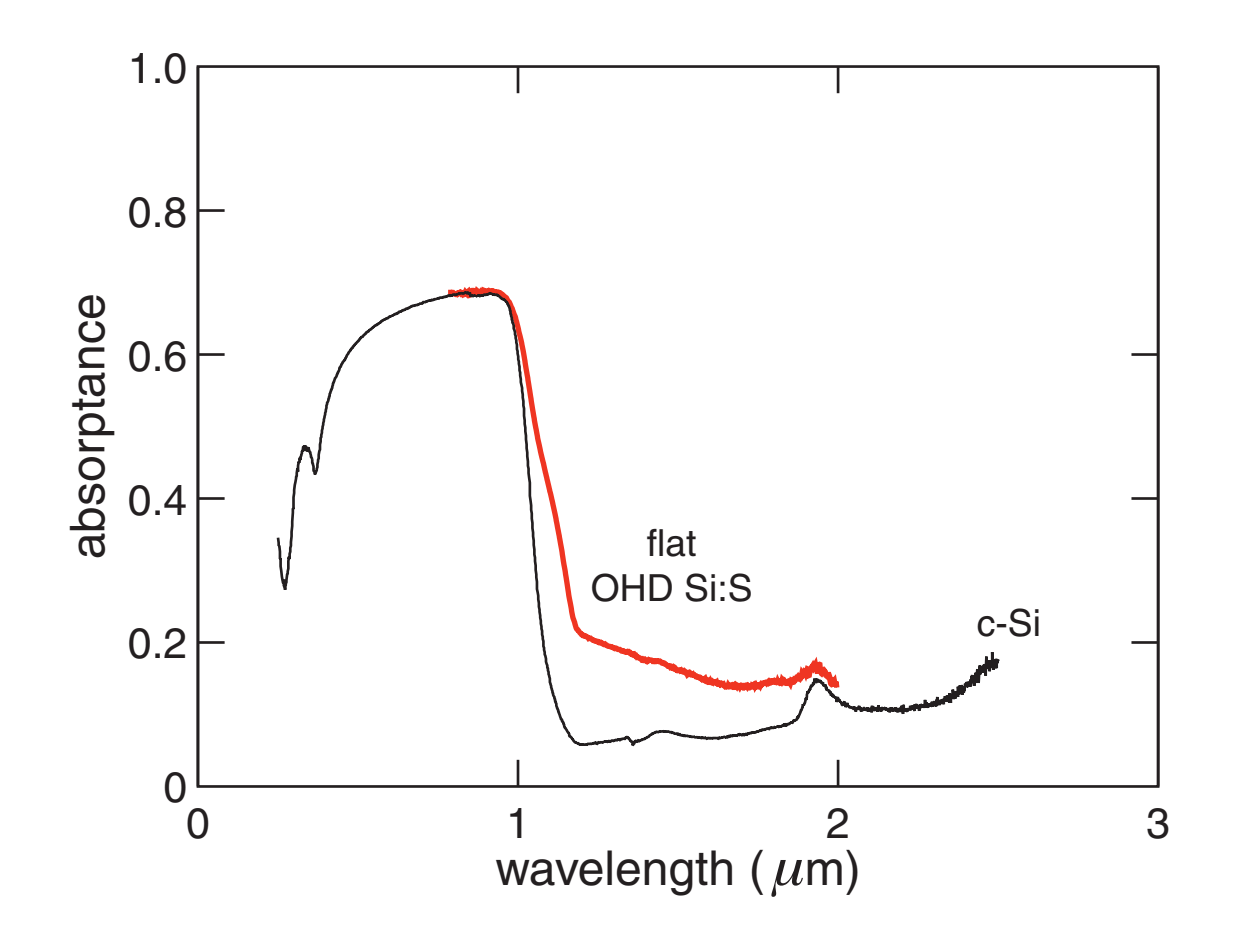


Optical hyperdoping



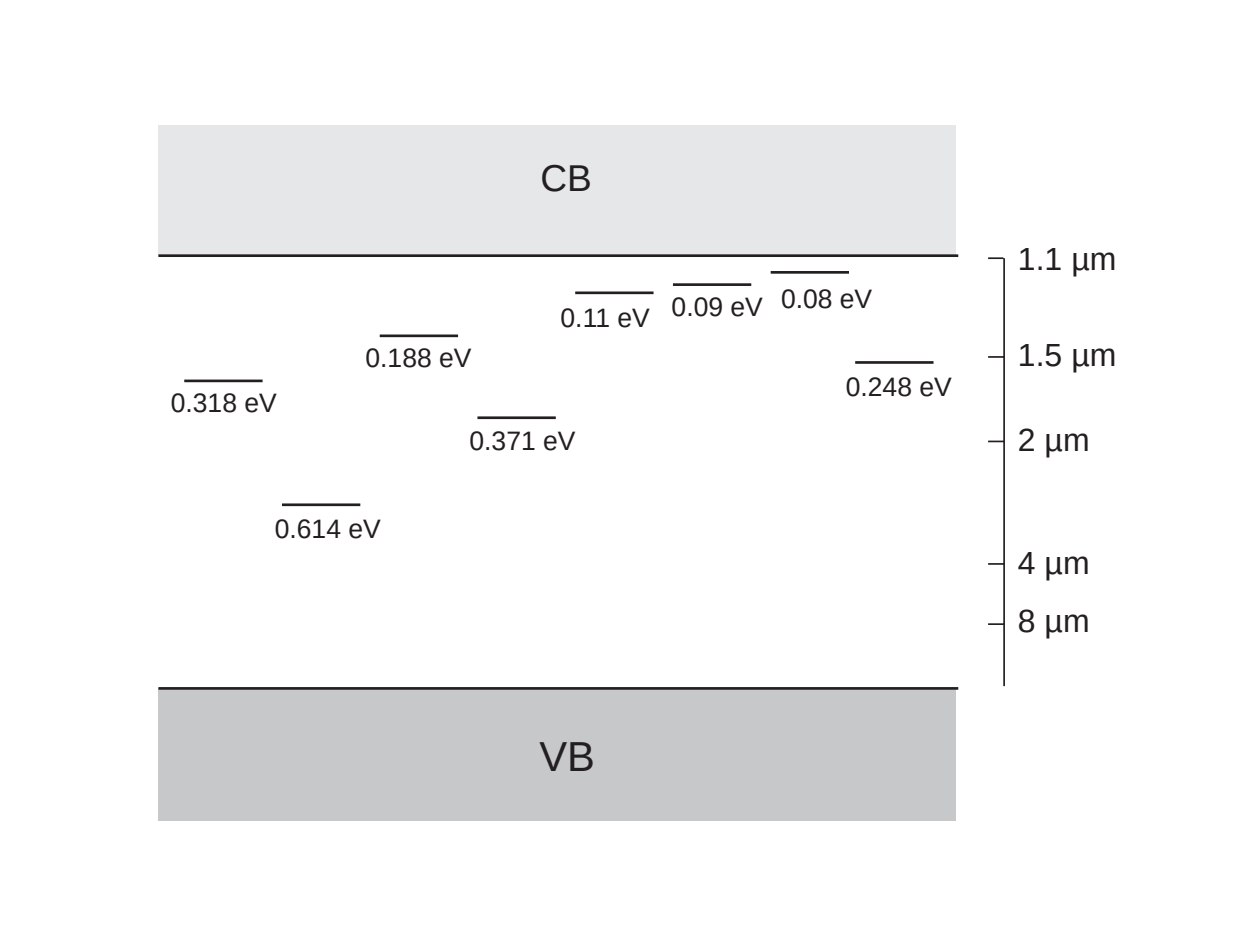
Optical hyperdoping

‘flat black silicon’ preserves IR absorption



Optical hyperdoping

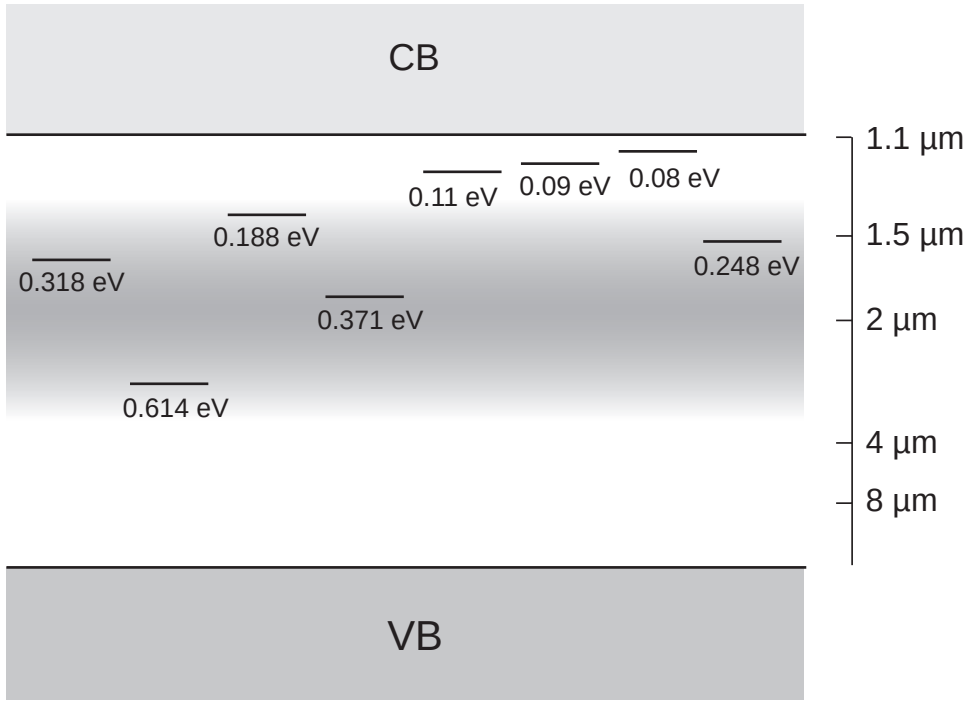
1 part in 10^6 sulfur introduces states in gap



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

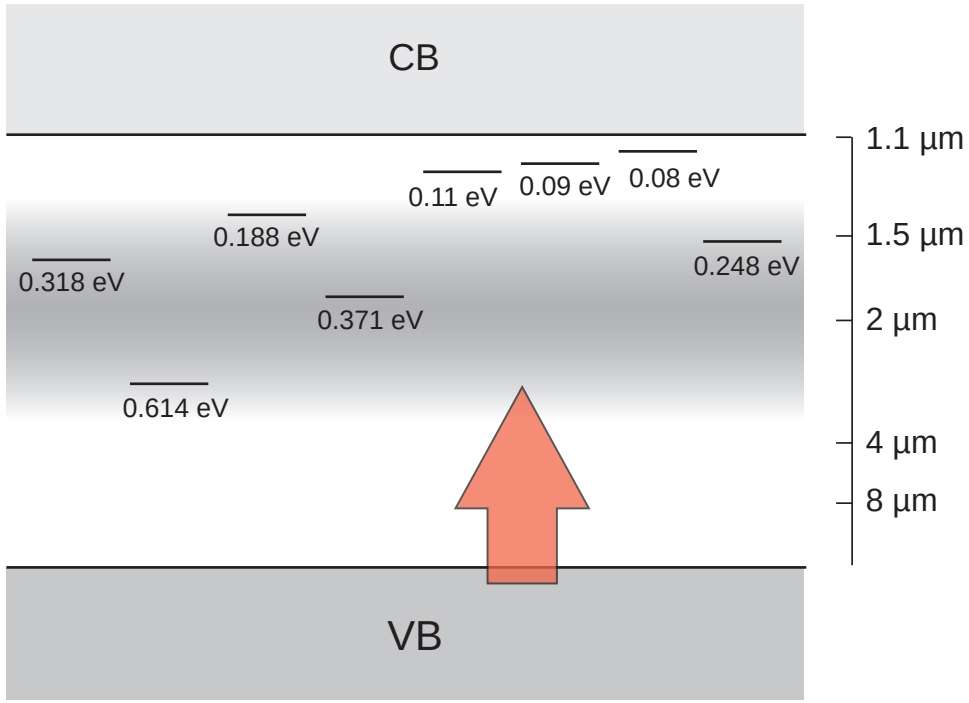
Optical hyperdoping

at high concentration states broaden into band



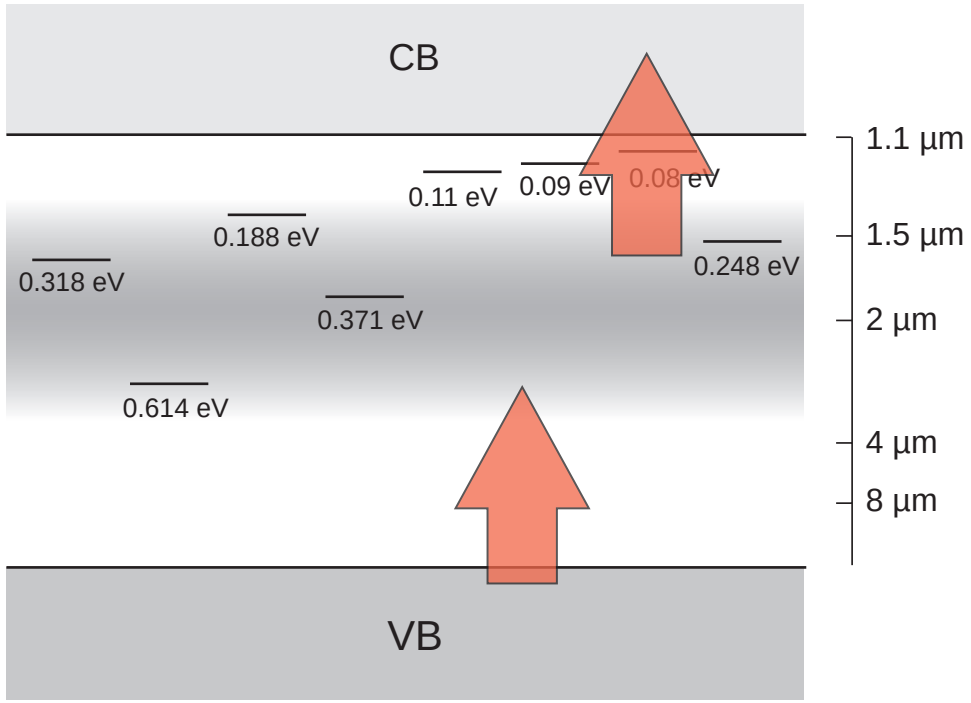
Optical hyperdoping

absorption extends into infrared



Optical hyperdoping

donor or acceptor states, depending on Fermi level



Optical hyperdoping

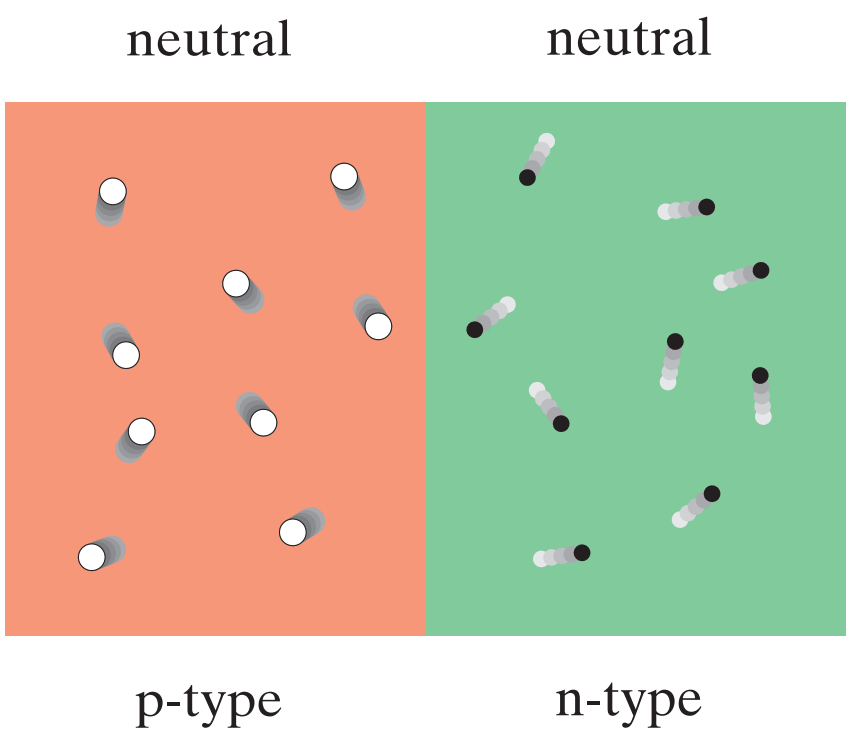
Things to keep in mind

- new chemical structure and electronic properties
- nanocrystallinity: quantum confinement effects
- absorption happens in nanocrystalline layer

Outline

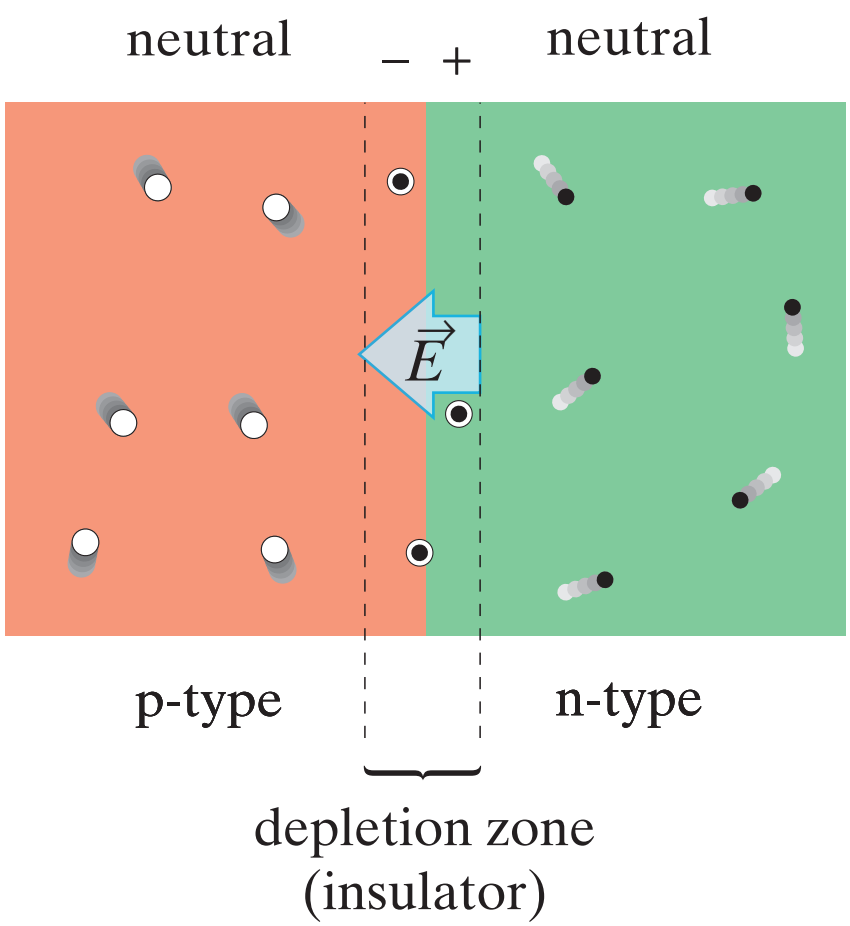
- Optical hyperdoping
- **photoelectron generation**
- photoconductive gain

Photoelectron generation



join acceptor and donor type Si…

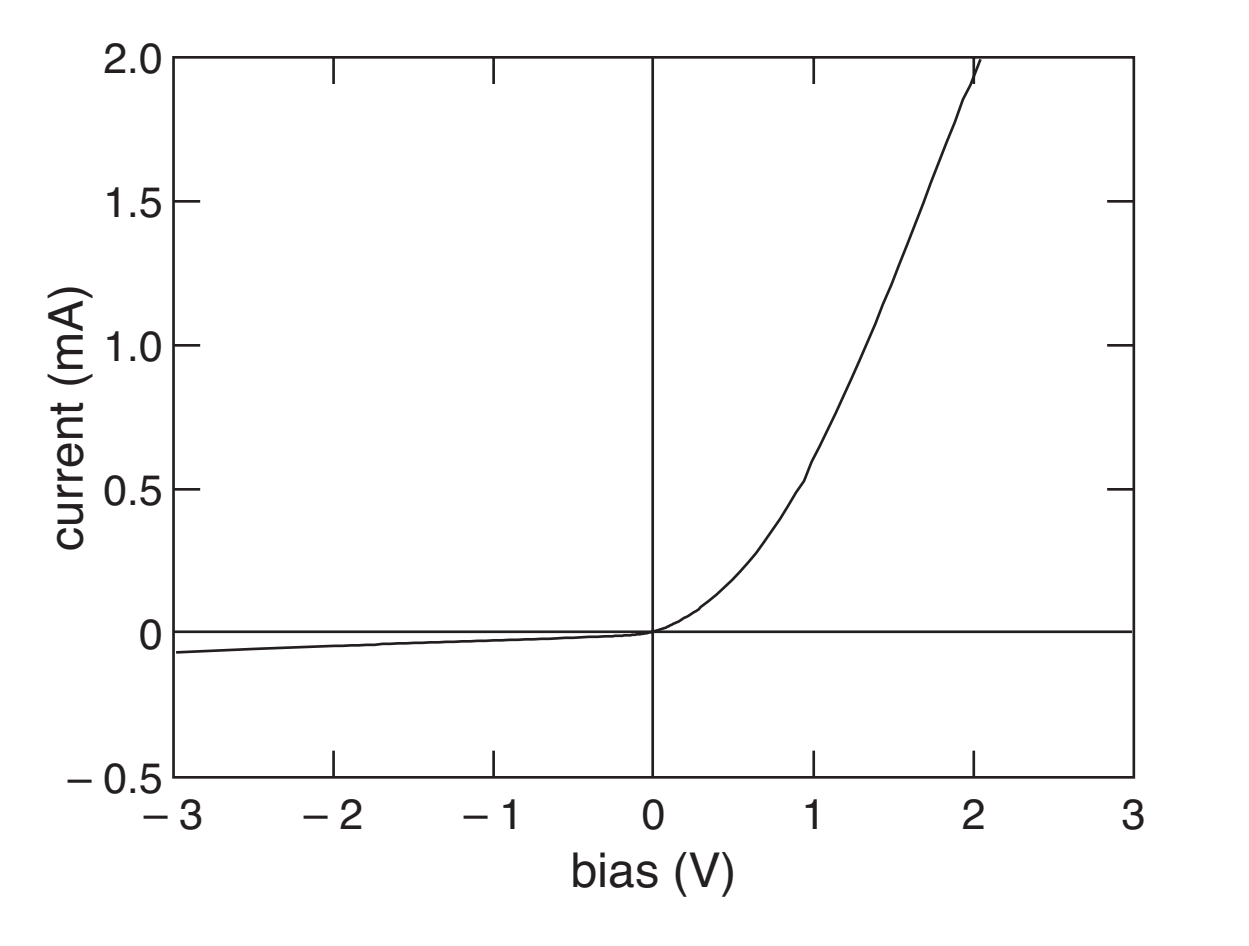
Photoelectron generation



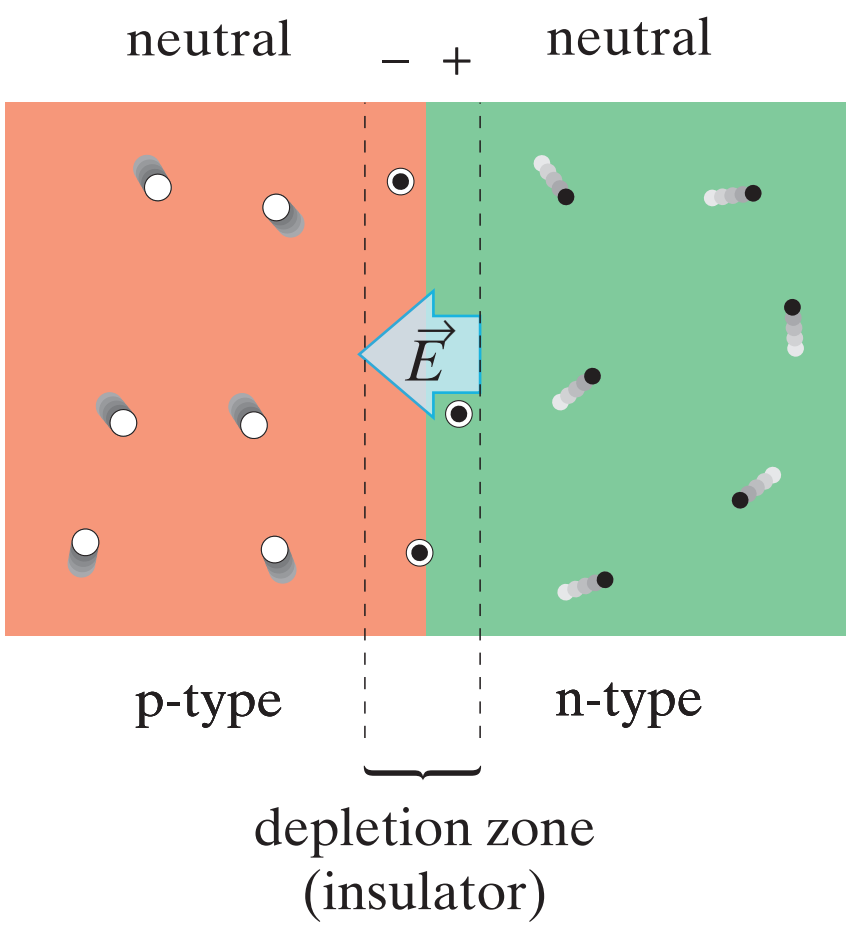
non-conducting layer at junction

Photoelectron generation

IV characteristics

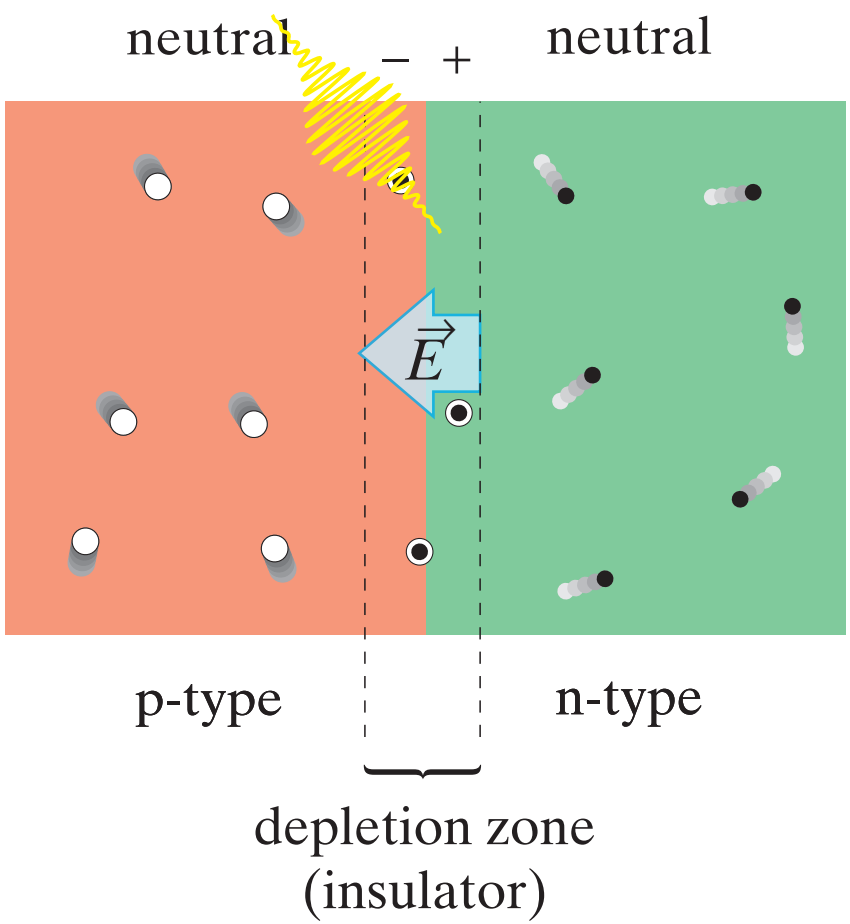


Photoelectron generation



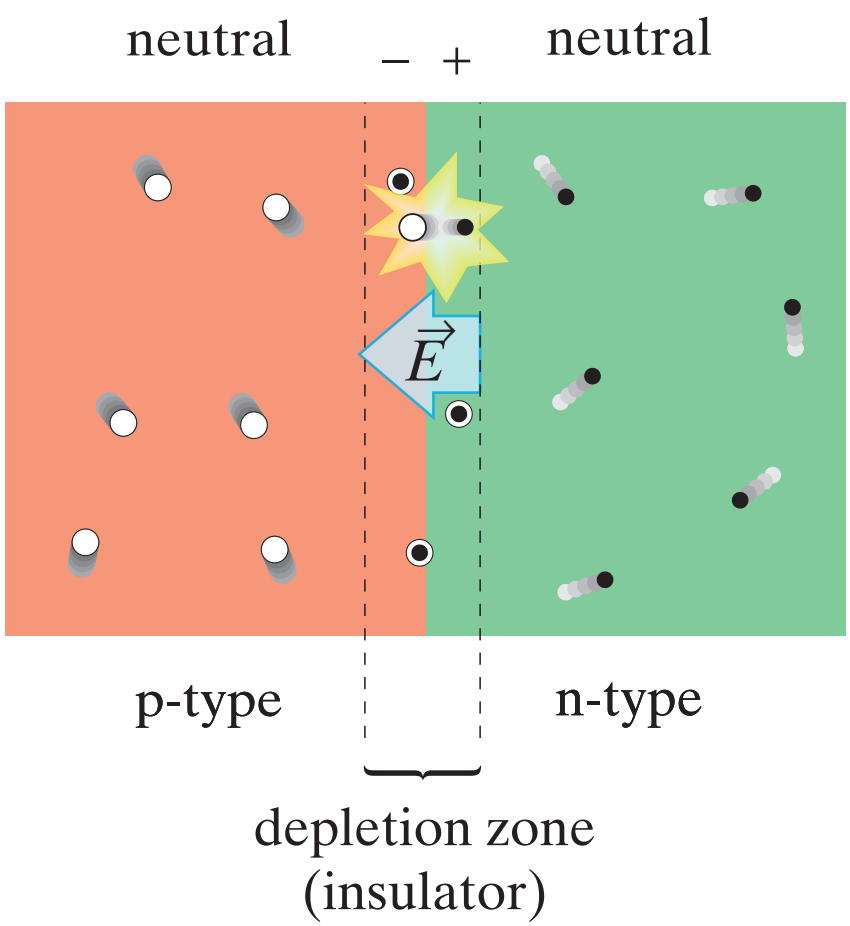
depletion layer can convert light into electric energy

Photoelectron generation



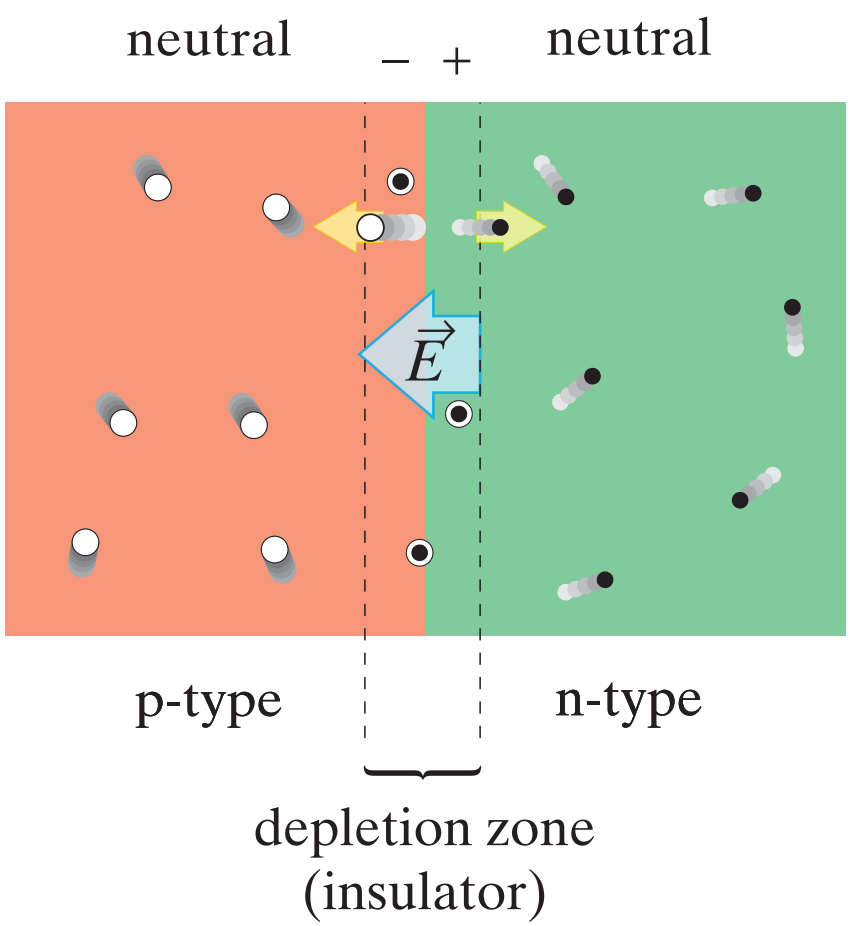
incident photon knocks out electron…

Photoelectron generation



…creating an electron-hole pair

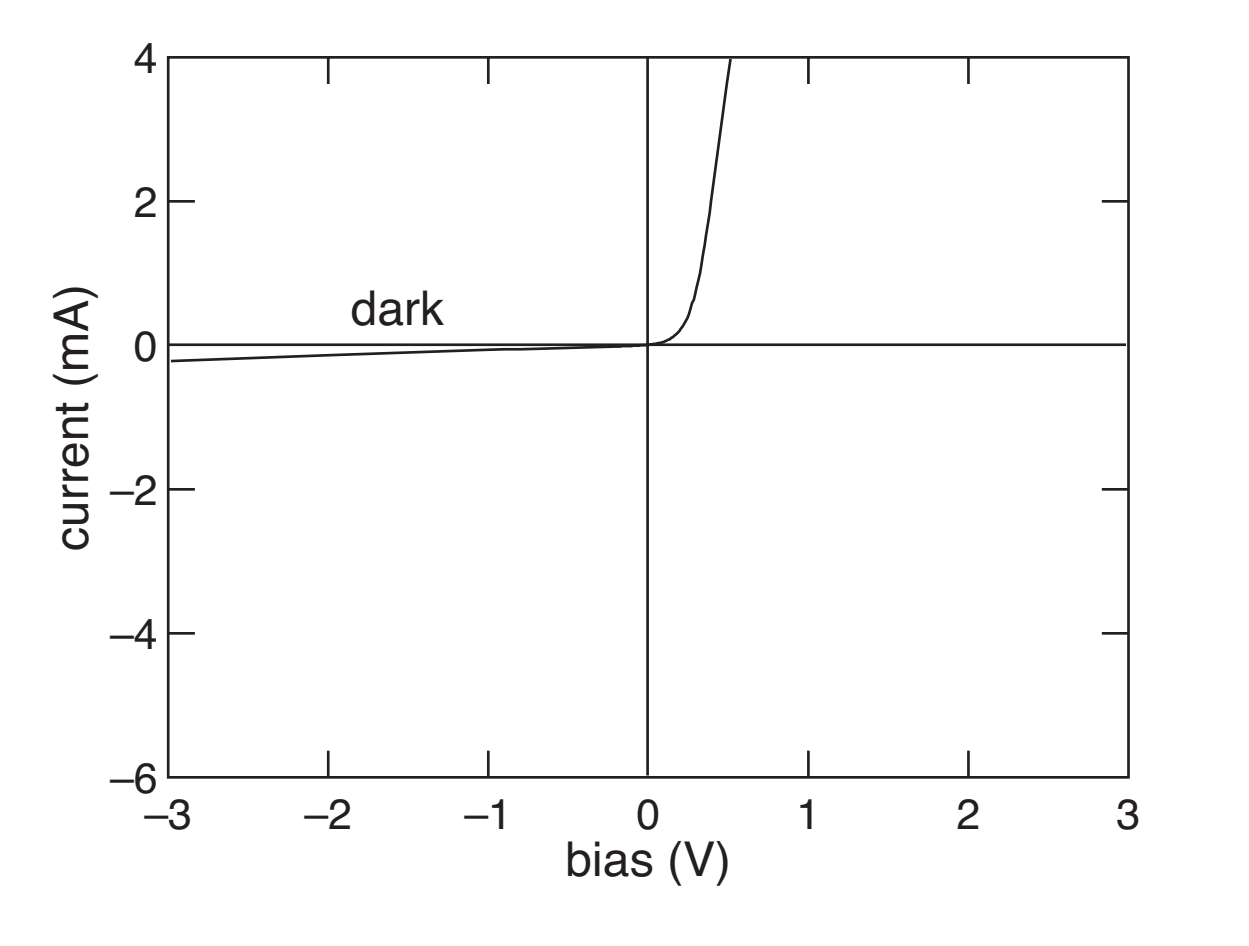
Photoelectron generation



E-field separates eh-pair, causing current

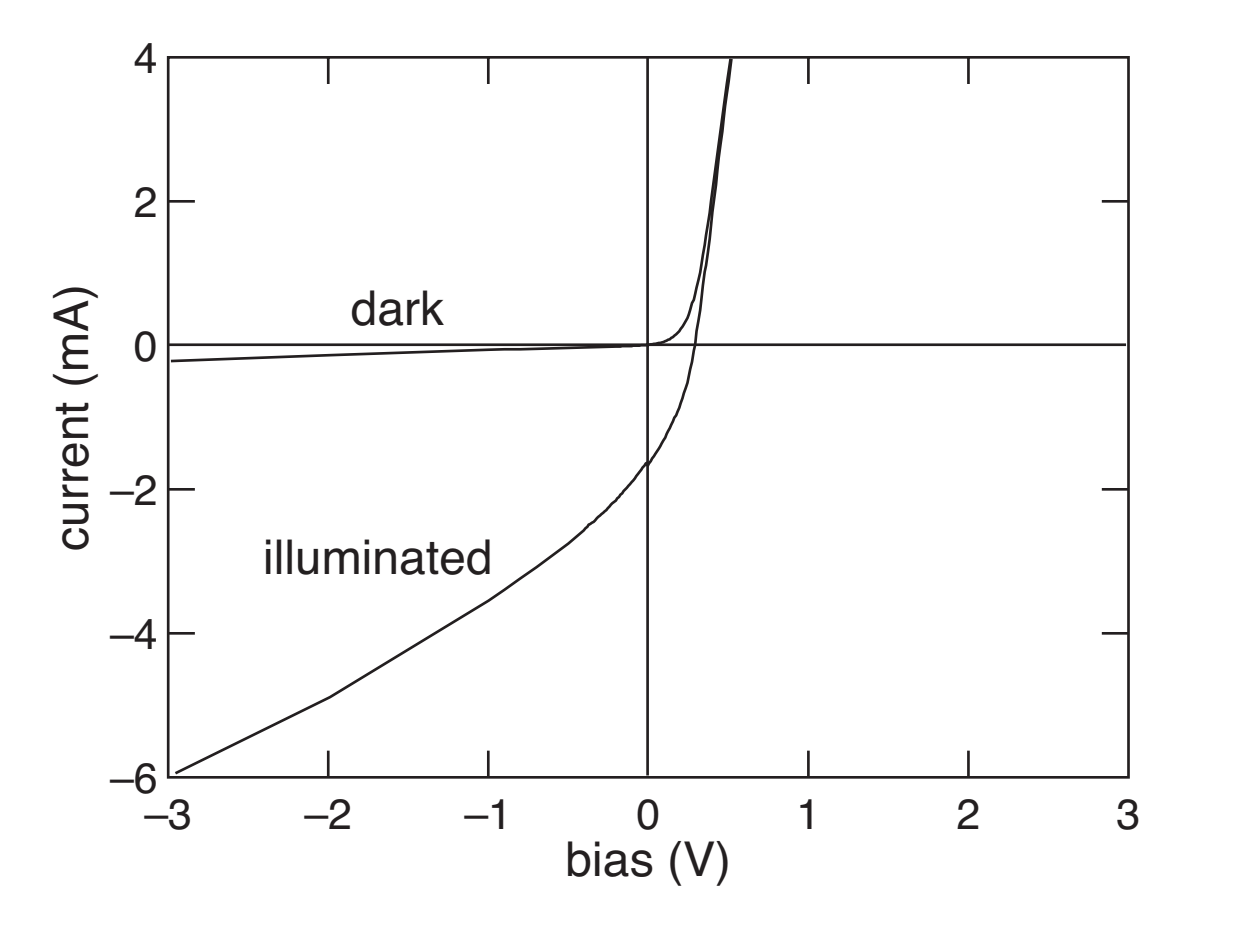
Photoelectron generation

IV characteristics



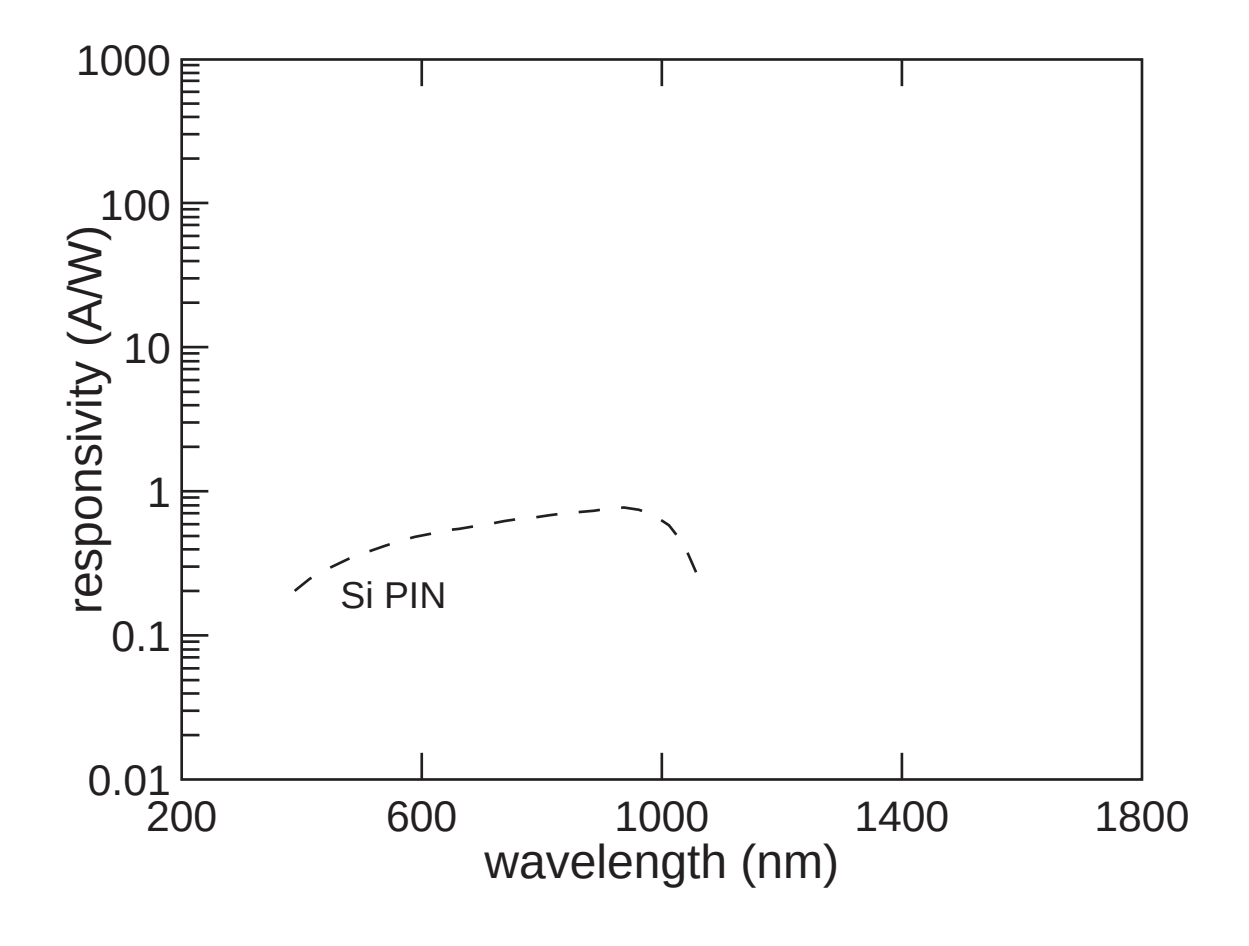
Photoelectron generation

IV characteristics



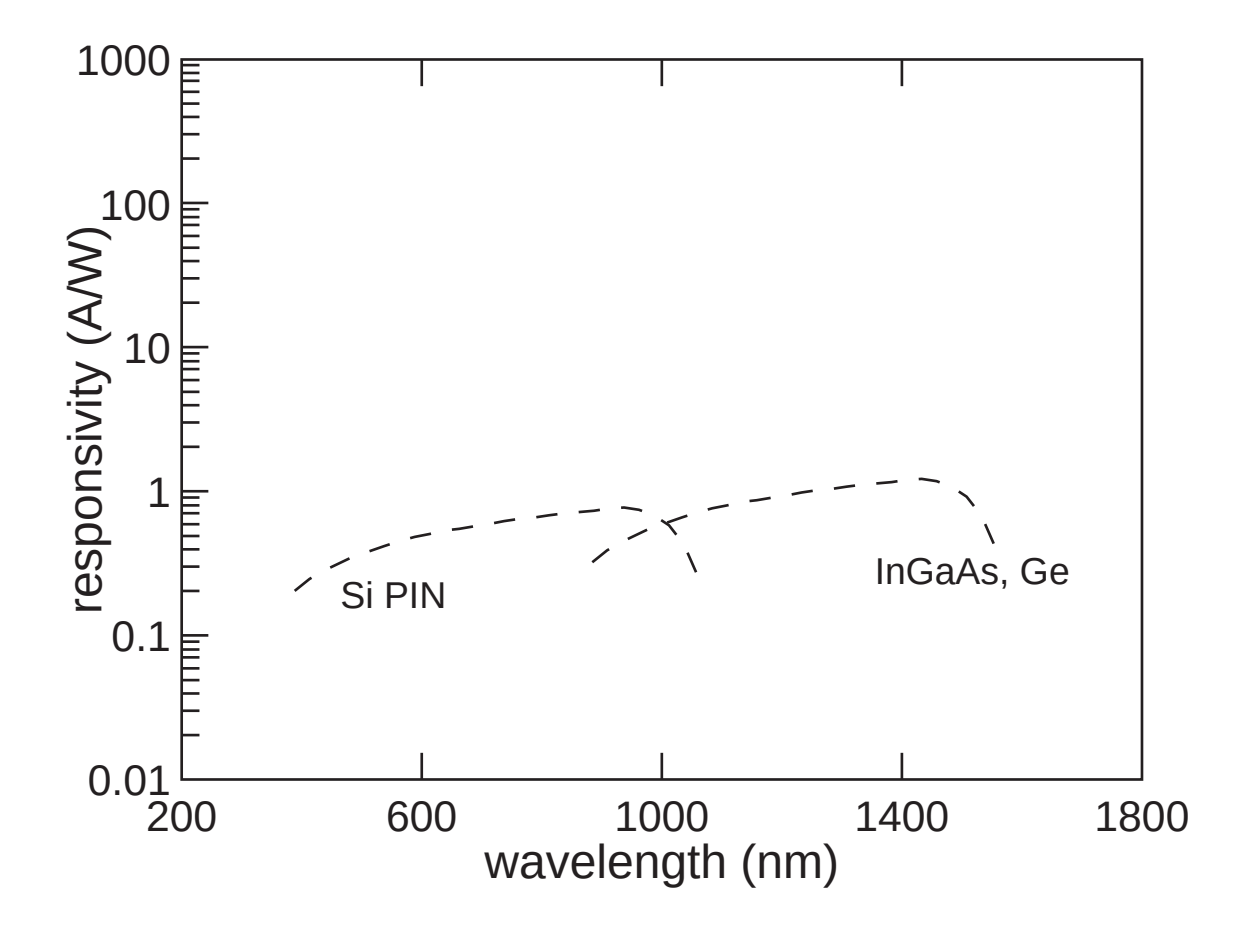
Photoelectron generation

responsivity



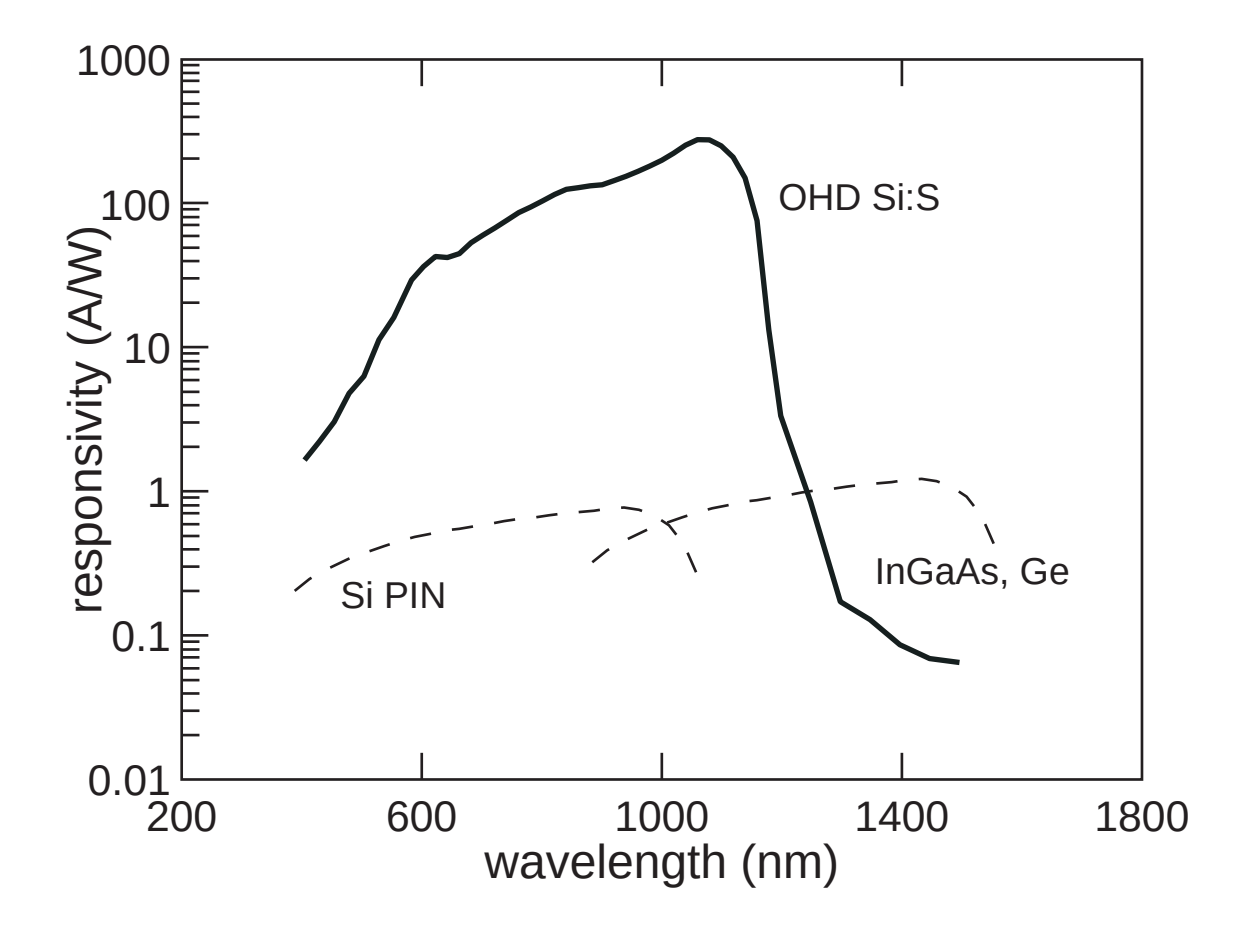
Photoelectron generation

responsivity



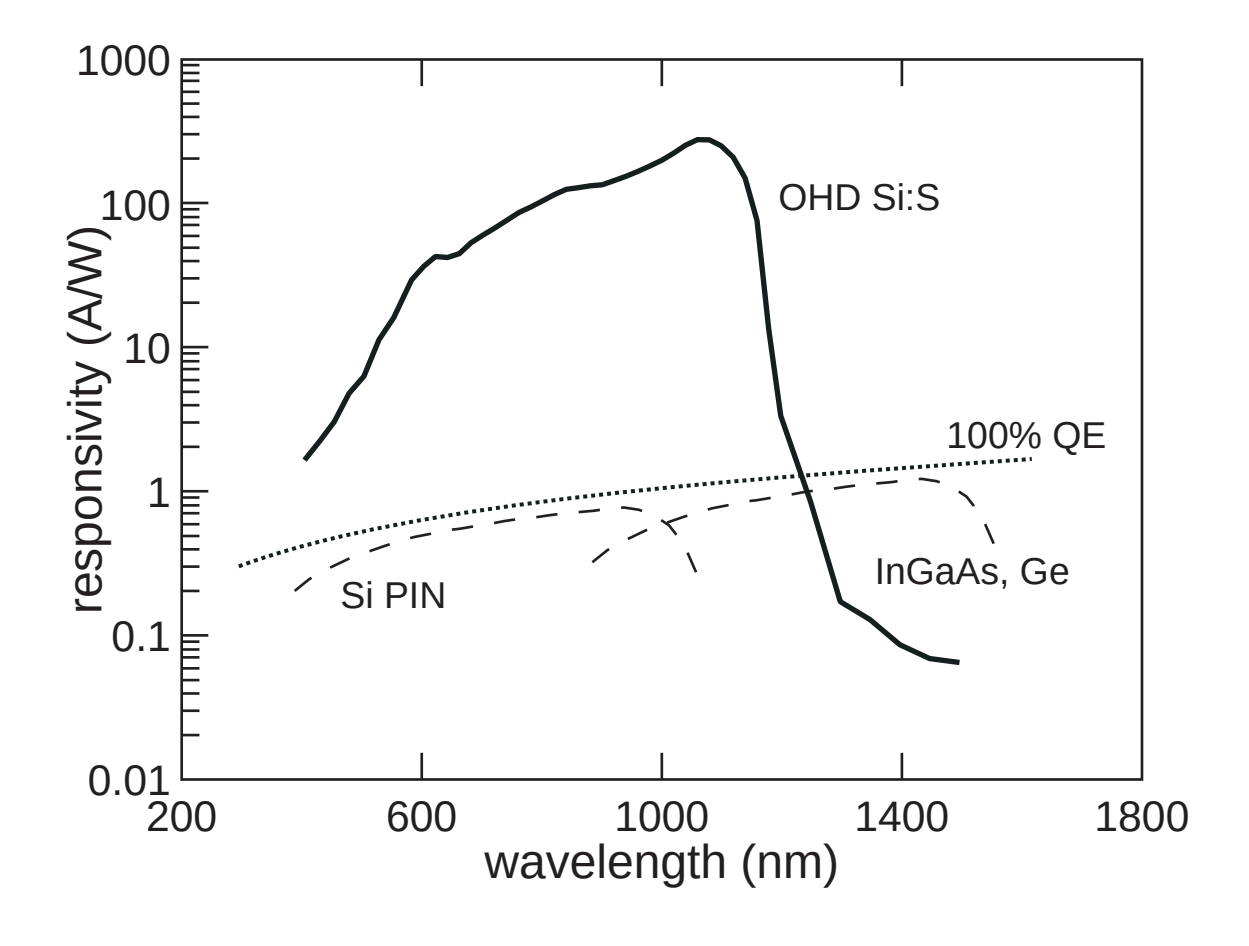
Photoelectron generation

responsivity



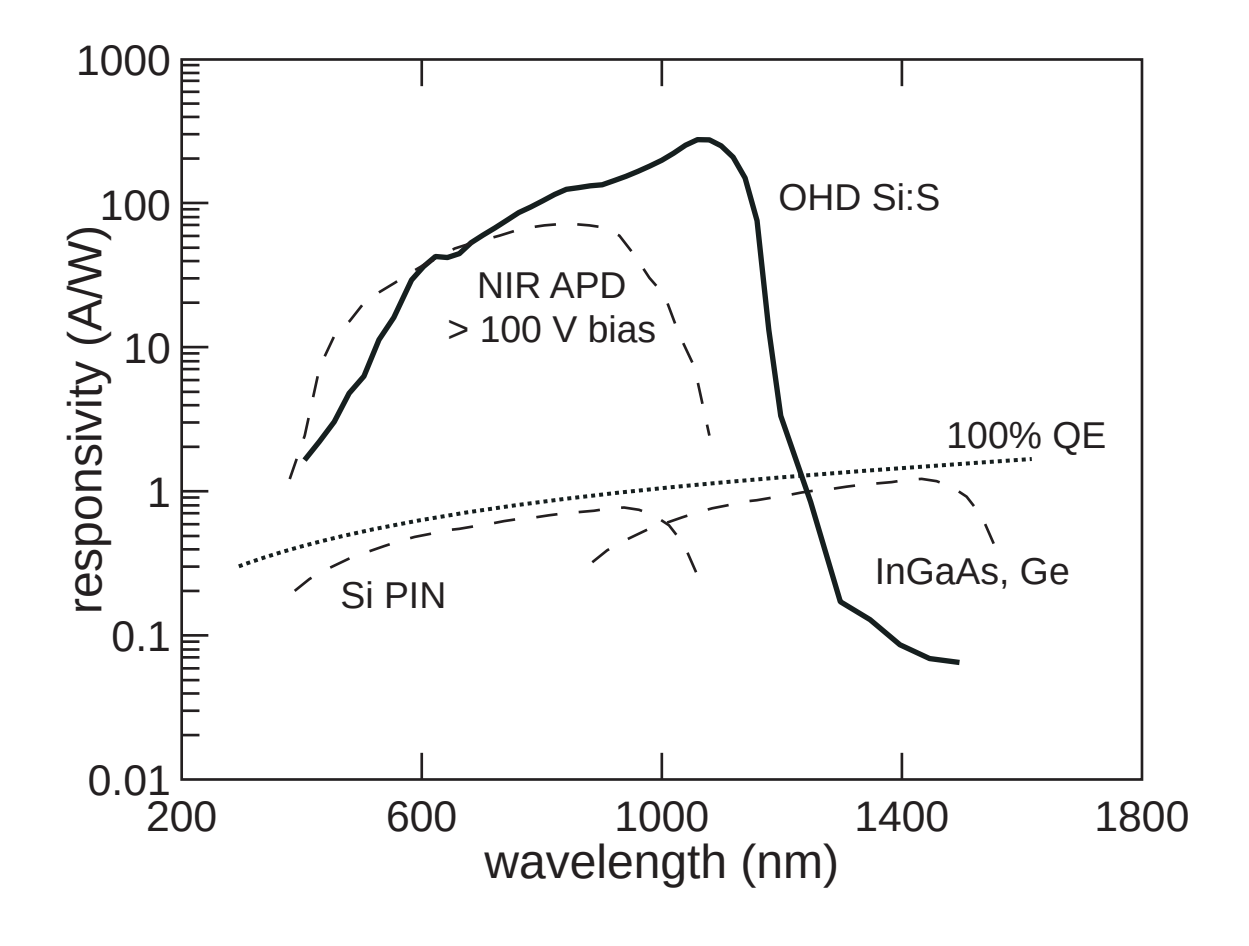
Photoelectron generation

responsivity



Photoelectron generation

responsivity



Photoelectron generation

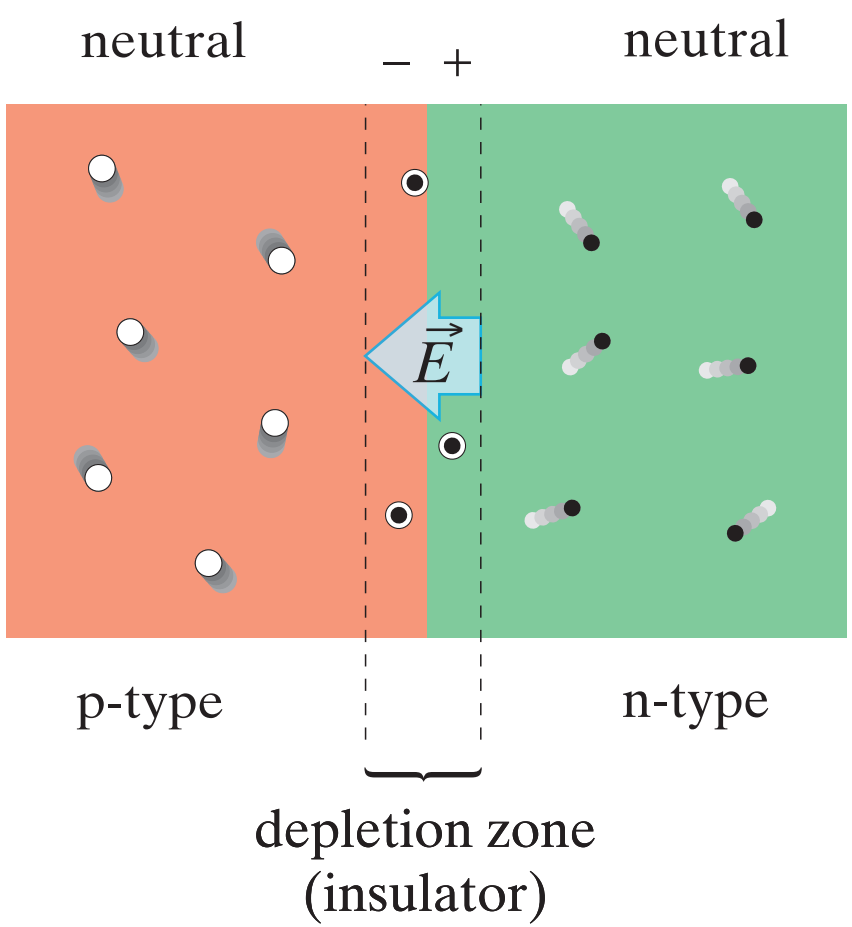
Things to keep in mind

- can turn absorption into photoelectrons
- very high responsivity in VIS and IR
- quantum efficiency larger than one

Outline

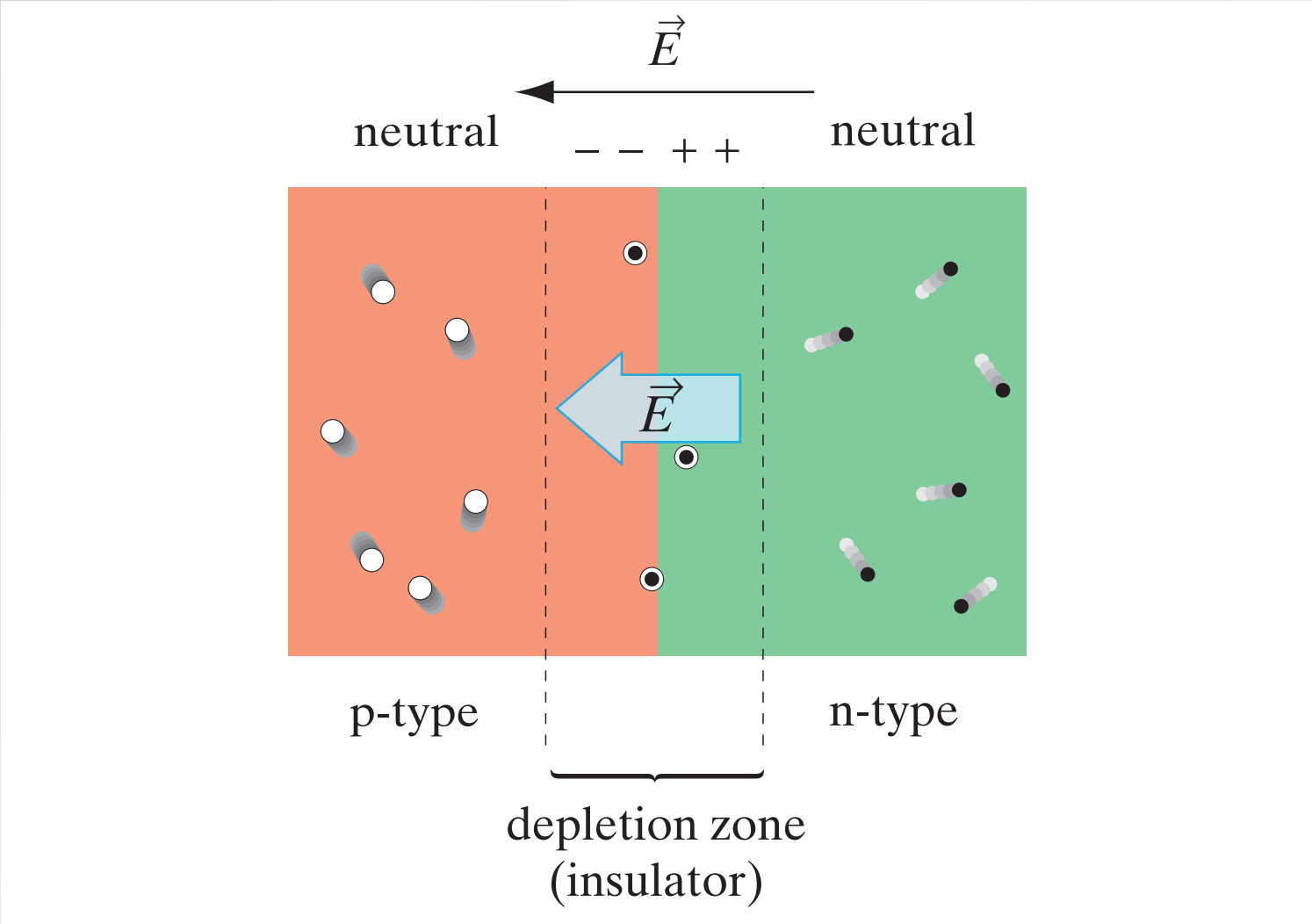
- Optical hyperdoping
- photoelectron generation
- **photoconductive gain**

Photoconductive gain



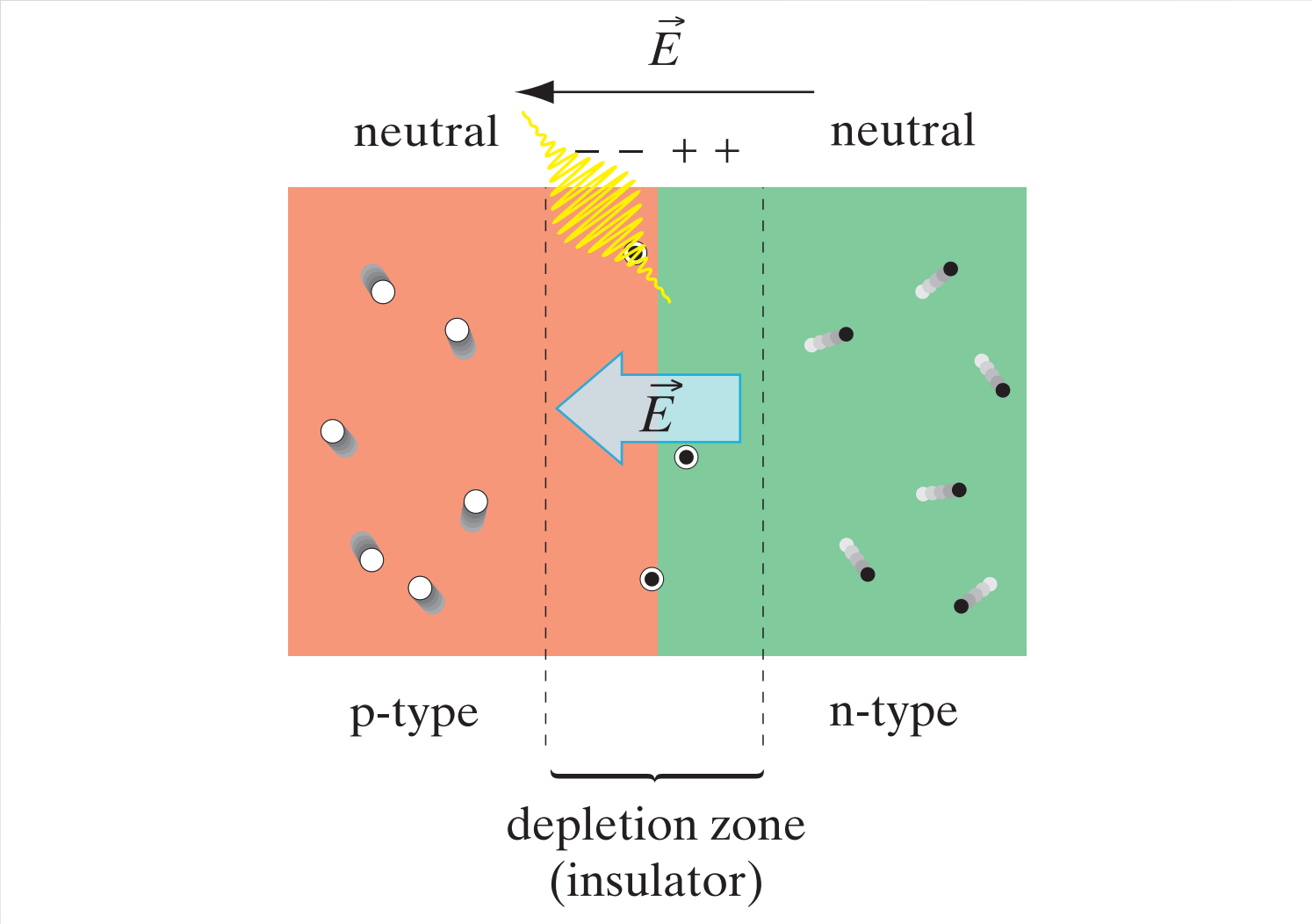
apply electric field…

Photoconductive gain



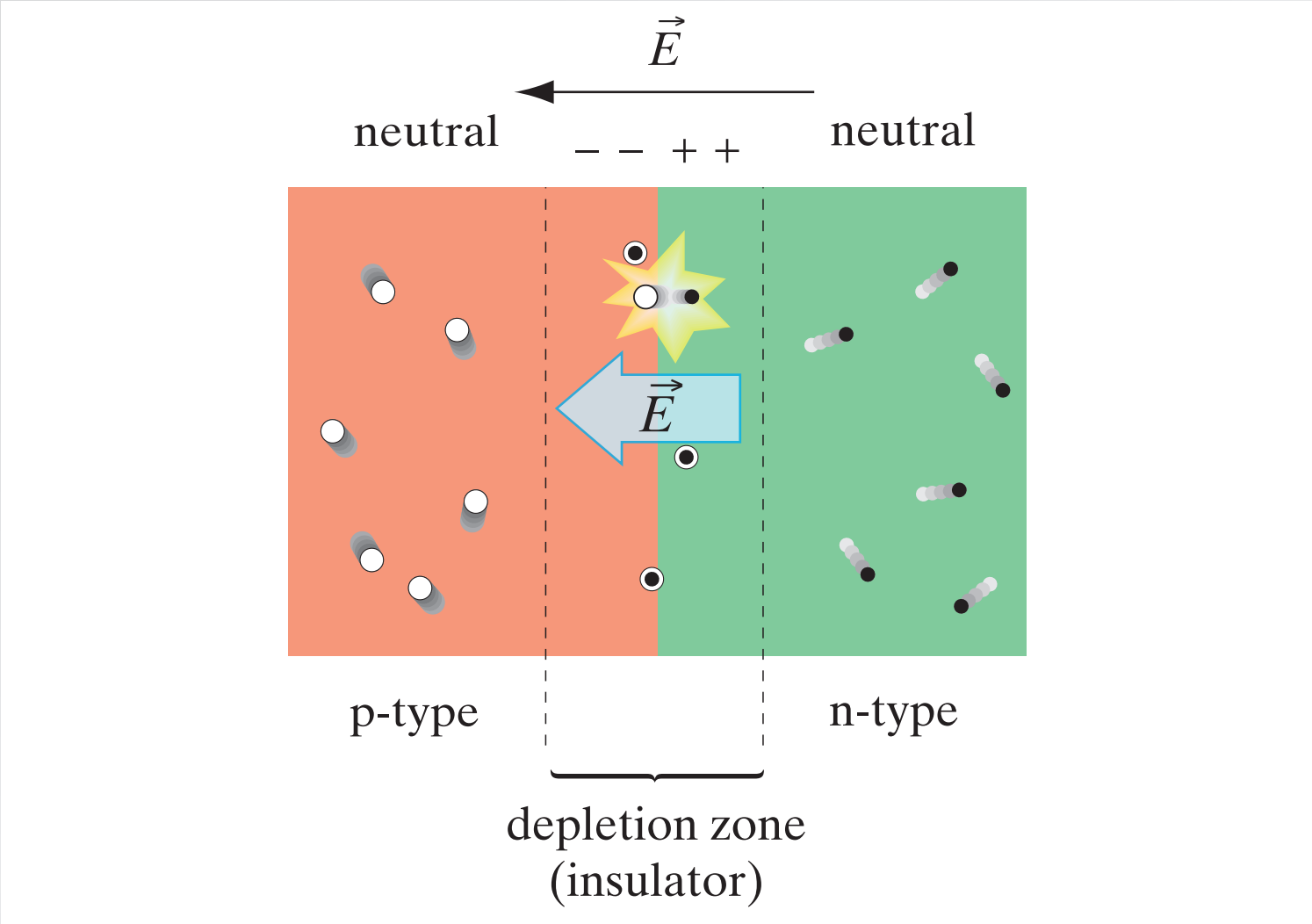
…and so depletion zone expands

Photoconductive gain



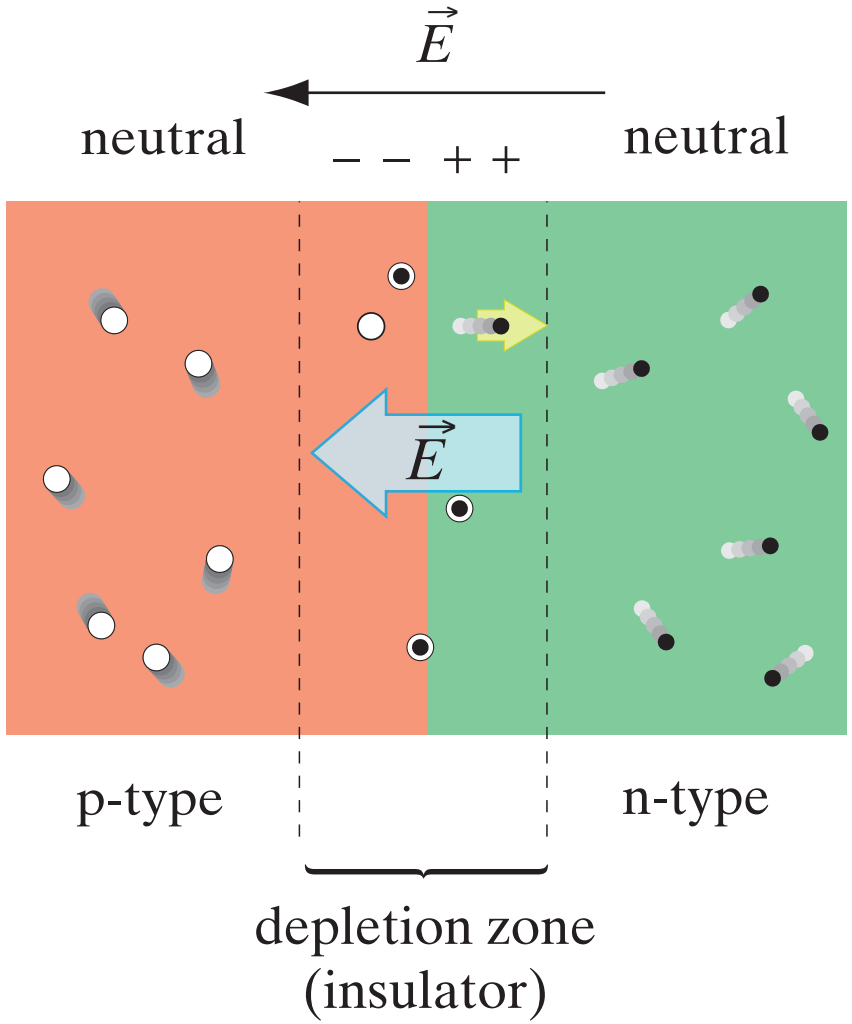
incident photon generates electron-hole pair

Photoconductive gain



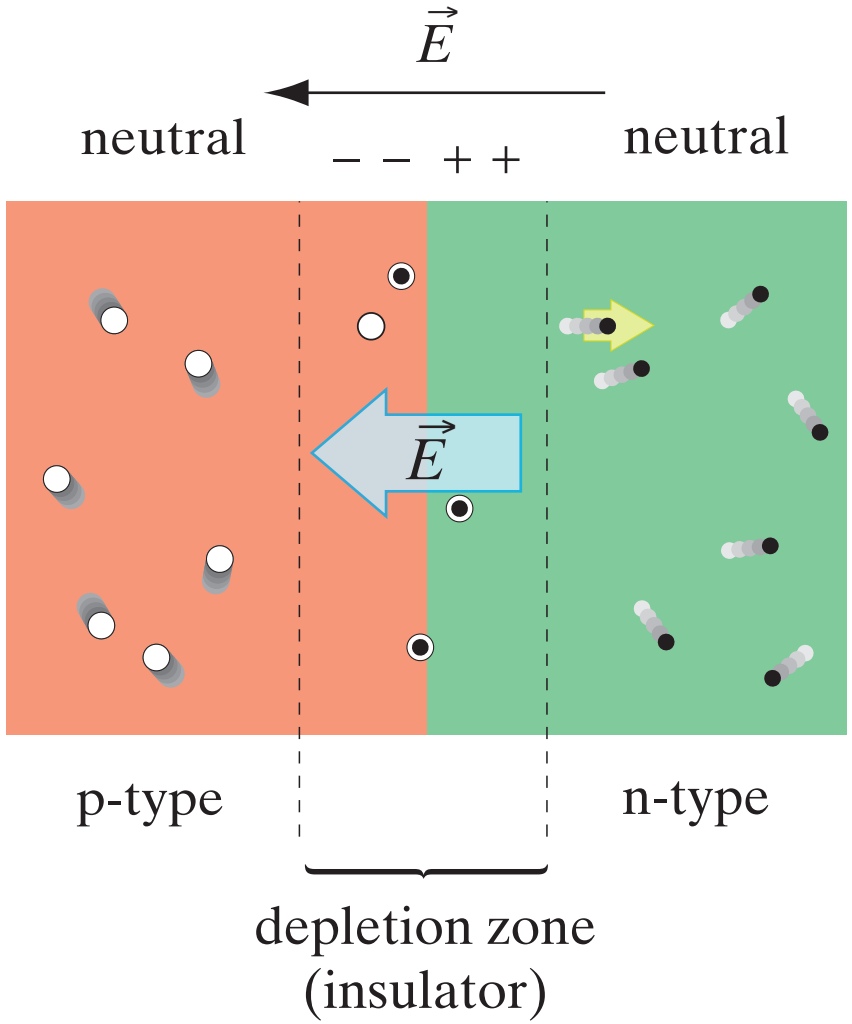
incident photon generates electron-hole pair

Photoconductive gain



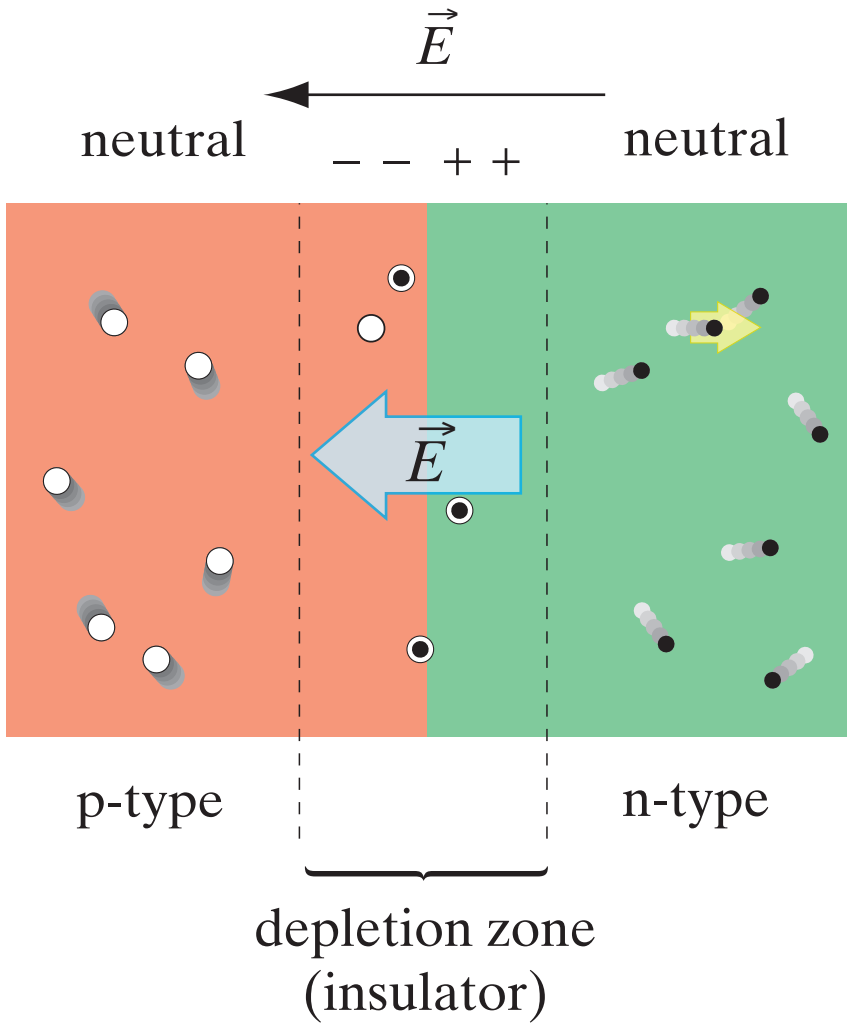
hole is trapped, electron accelerates…

Photoconductive gain



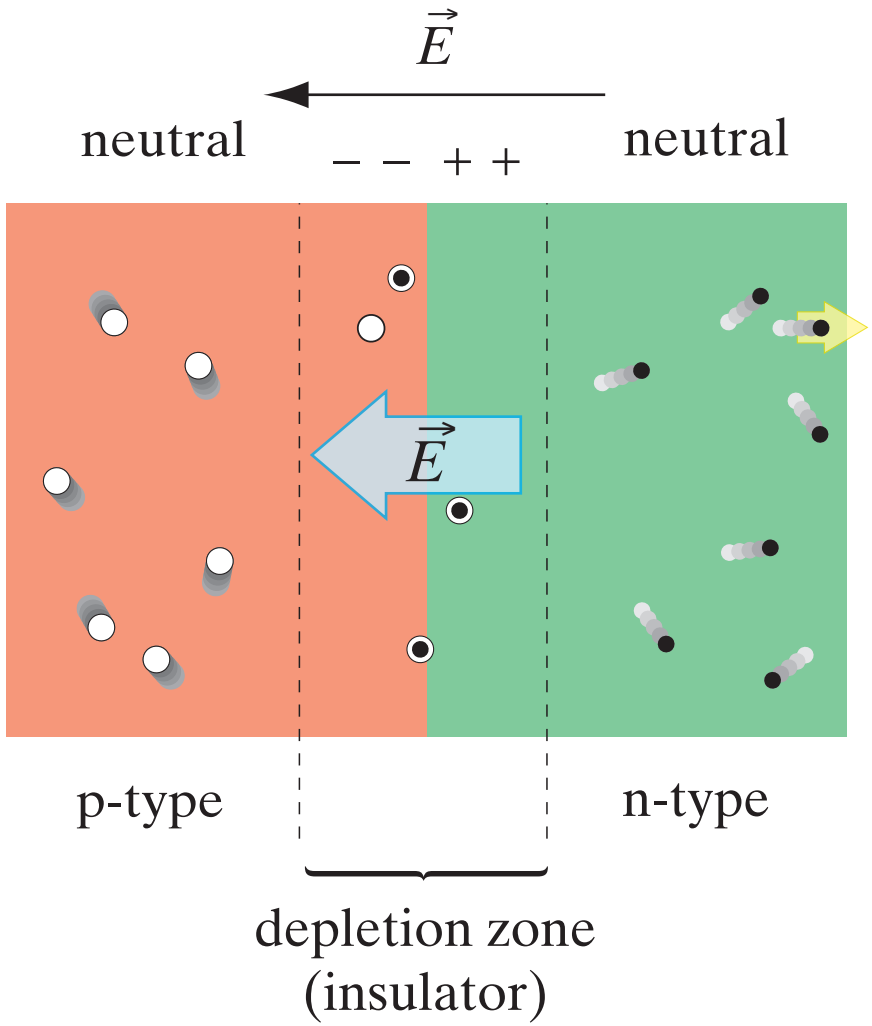
hole is trapped, electron accelerates…

Photoconductive gain



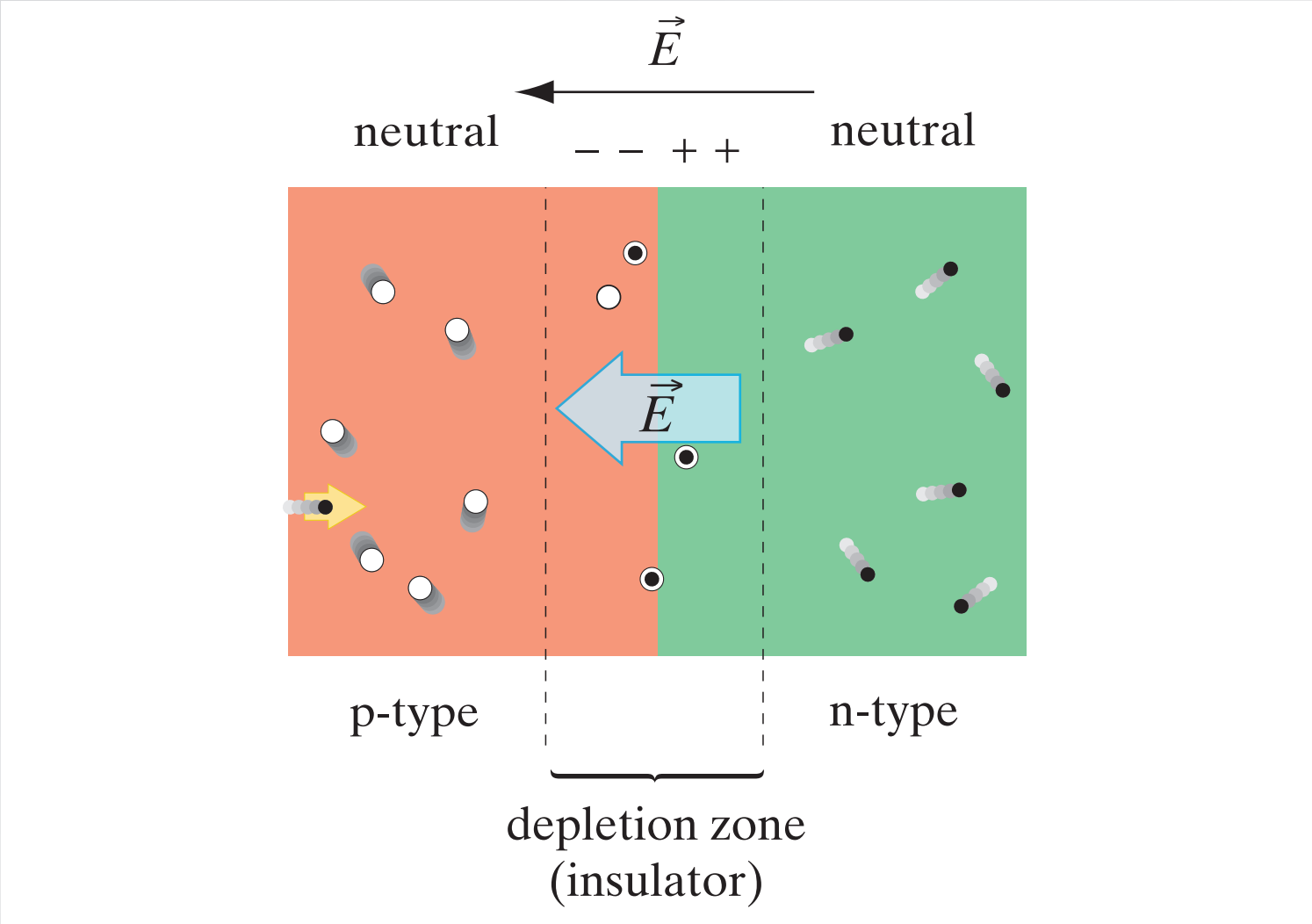
hole is trapped, electron accelerates…

Photoconductive gain



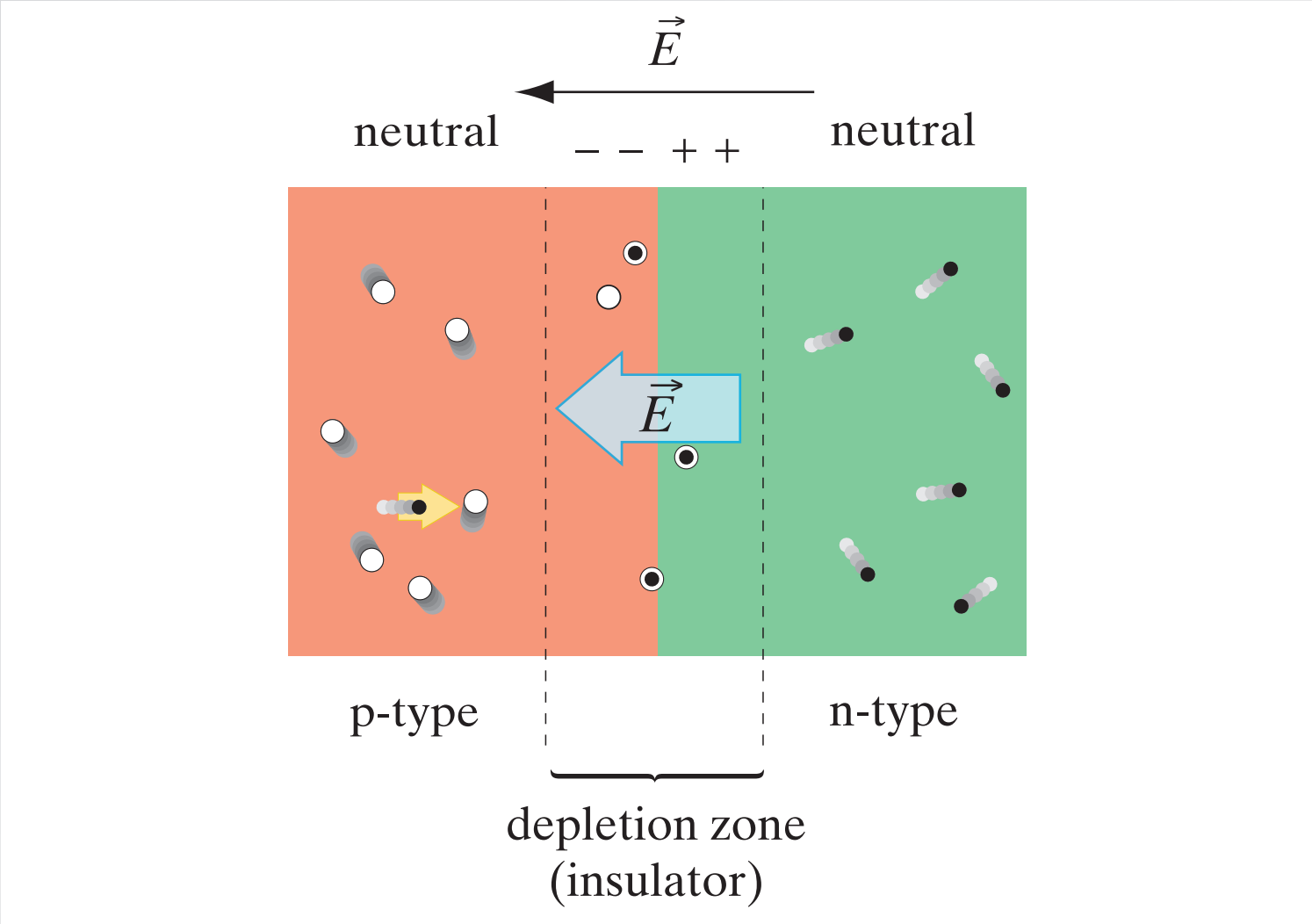
…exits sample…

Photoconductive gain



…and source supplies a new electron

Photoconductive gain



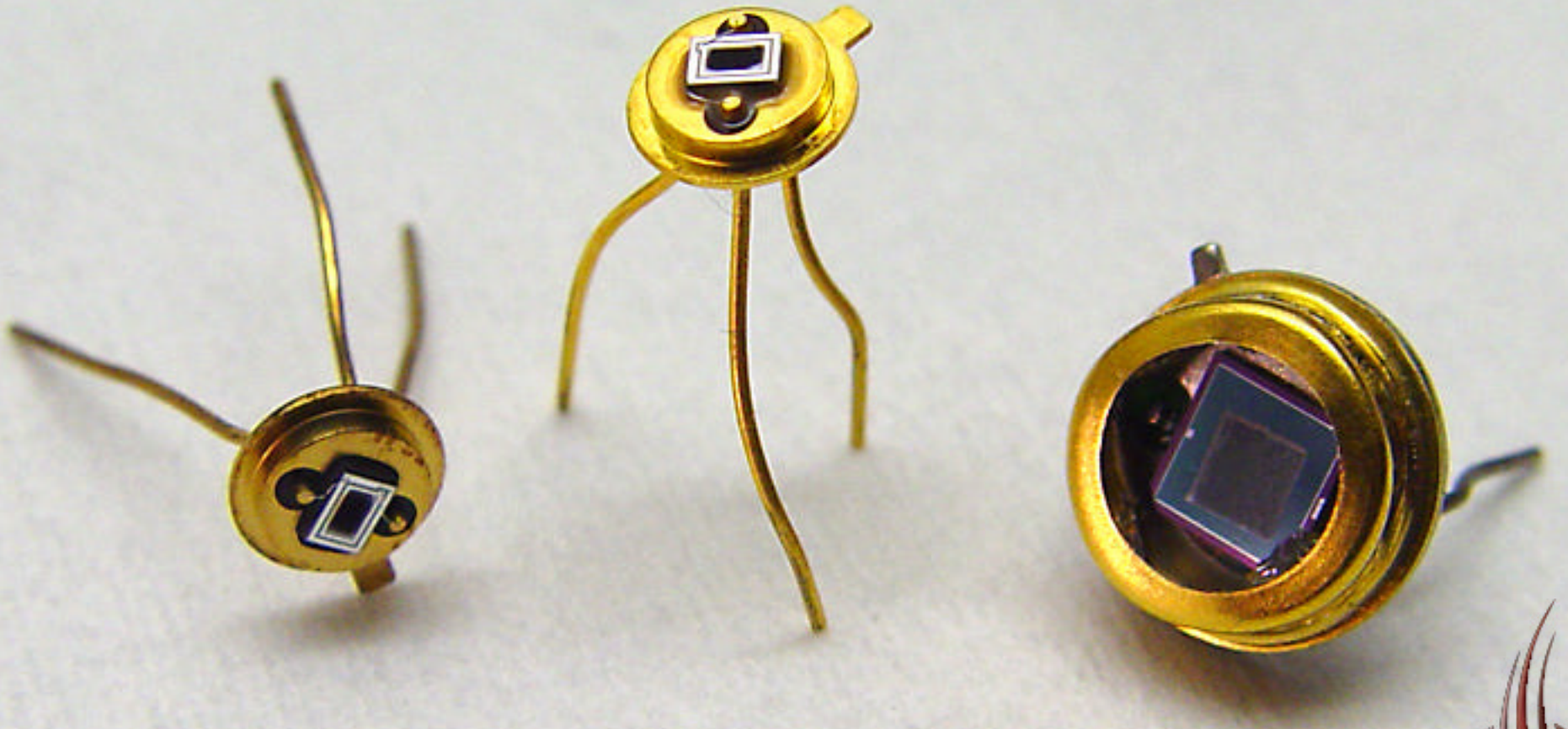
…and source supplies a new electron

Photoconductive gain

Things to keep in mind

- photoconductive gain at room temperature!
- significant promise as photovoltaic material

Photoconductive gain



http://www.sionyxinc.com

SiOnyx

Photoconductive gain

- low-voltage, high-responsivity detectors
- silicon-based IR detectors
- higher QE photovoltaic cells

http://www.sionyxinc.com

SiOnyx

Summary

Optical hyperdoping produces new class of material

Funding:

Army Research Office
DARPA
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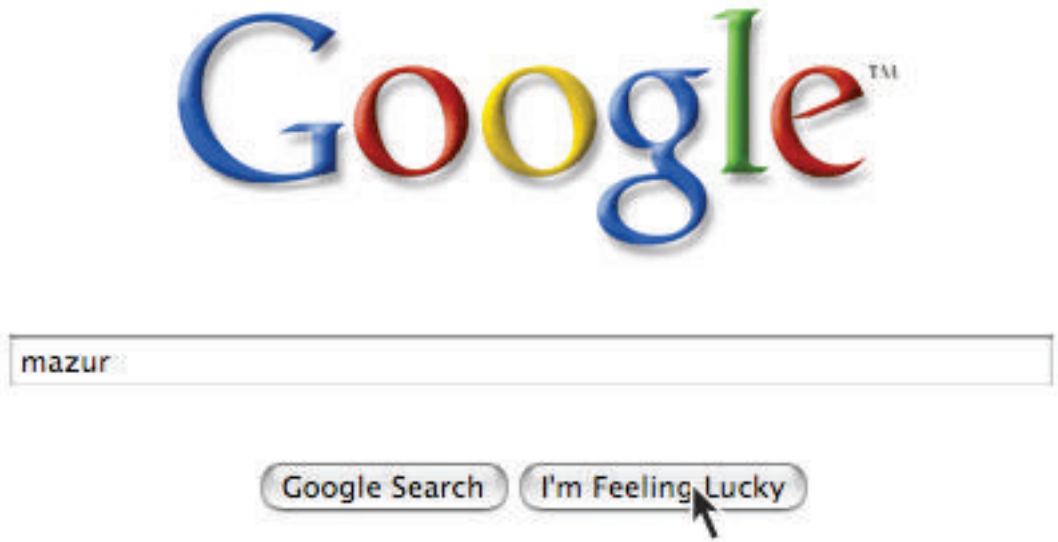
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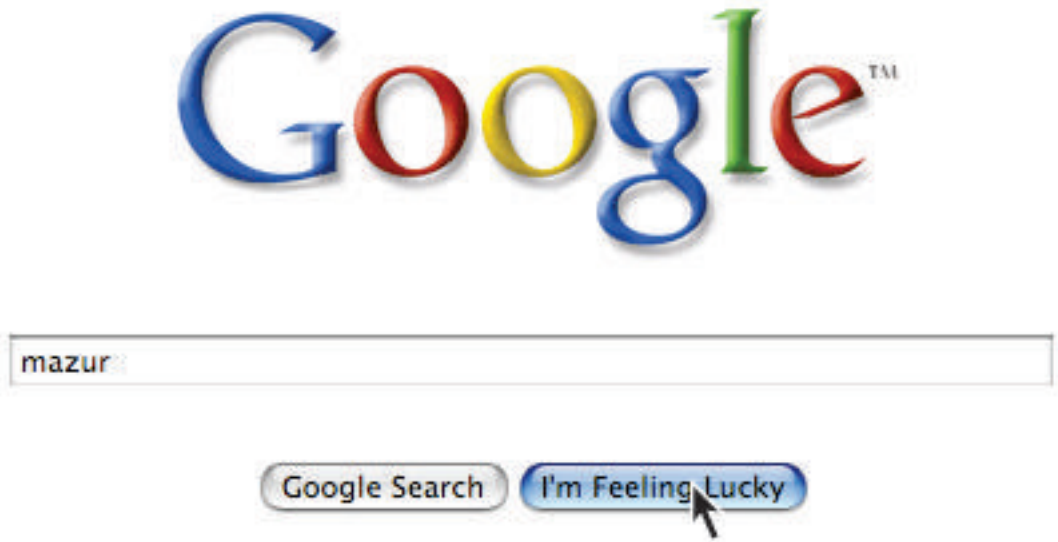
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