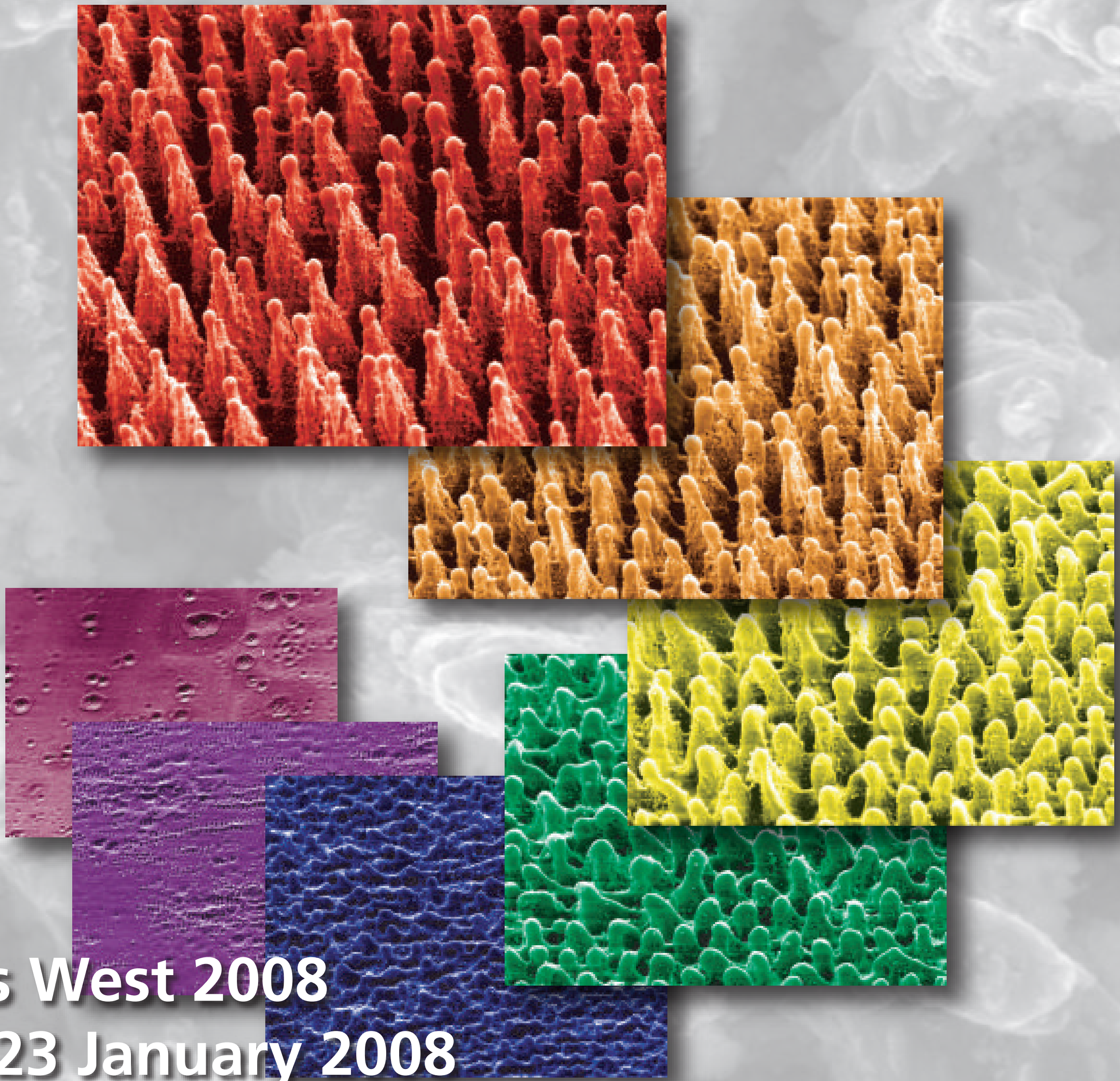
High photoconductive gain and broad spectral sensitivity by fs laser doping of silicon



SPIE Photonics West 2008
San Jose, CA, 23 January 2008


Eric Mazur


Mark Winkler


Eric Diebold


Brian Tull

and also....

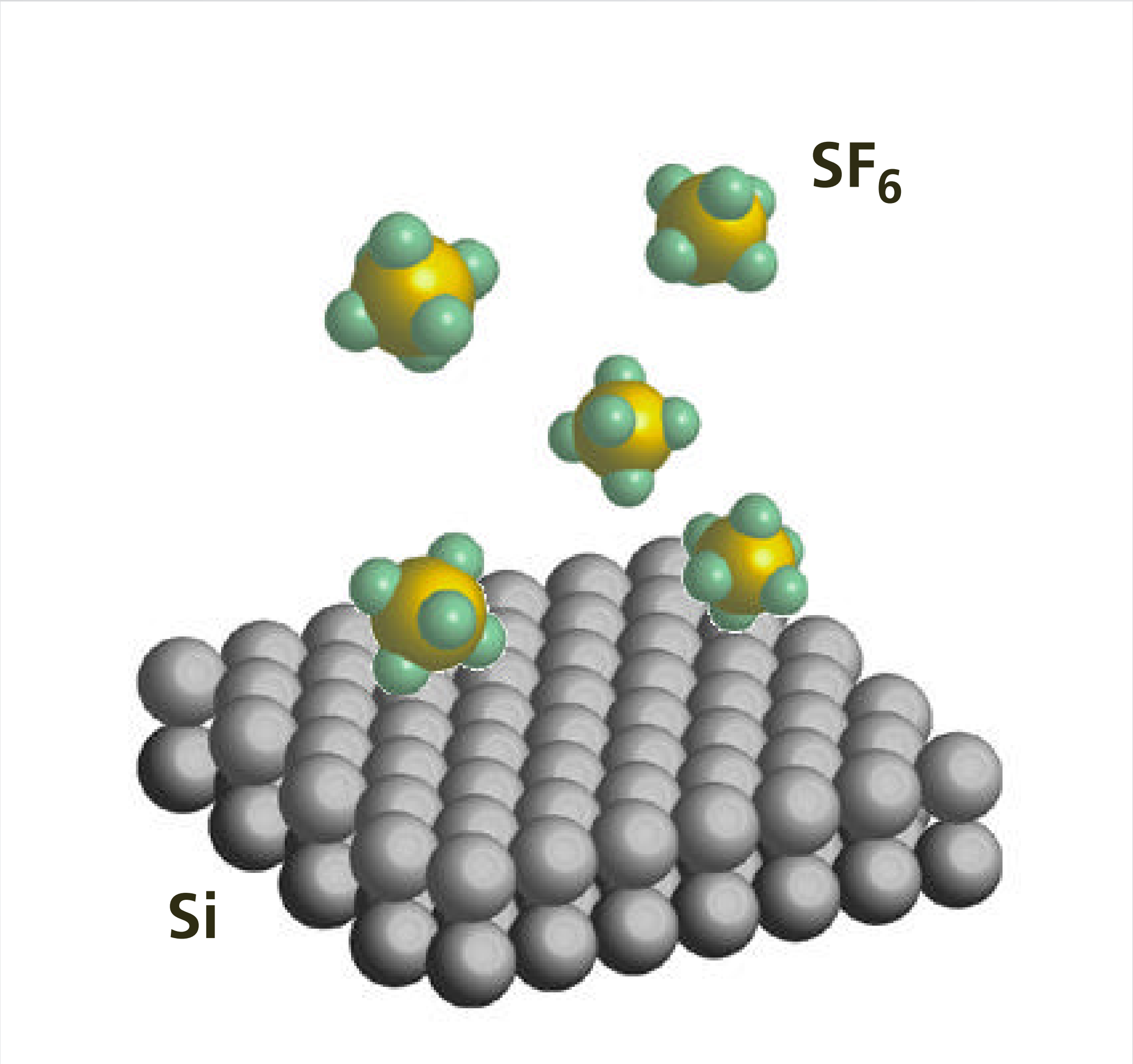
Dr. Jim Carey
Dr. Tsing-Hua Her
Dr. Shrenik Deliwala
Dr. Richard Finlay
Dr. Michael Sheehy
Dr. Jeffrey Warrander
Dr. Claudia Wu
Dr. Rebecca Younkin
Prof. Catherine Crouch
Prof. Mengyan Shen

Dr. John Chervinsky
Dr. Joshua Levinson

Dr. François Génin (LLNL)
Dr. Richard Farrell
Dr. Arieh Karger (RMD)
Dr. Richard Meyers (RMD)

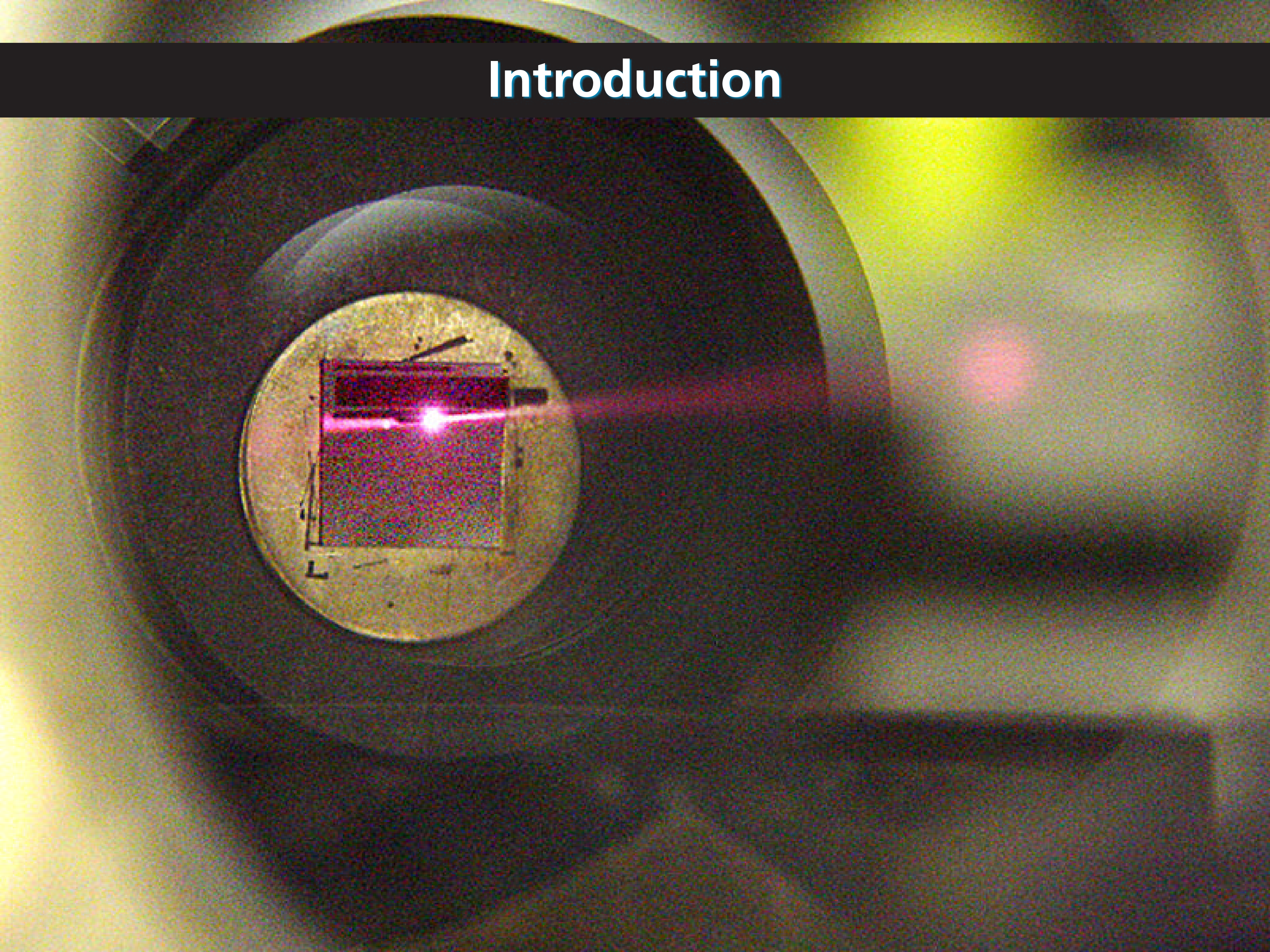
Prof. Michael Aziz
Prof. Cynthia Friend
Prof. Li Zhao (Fudan)

Introduction

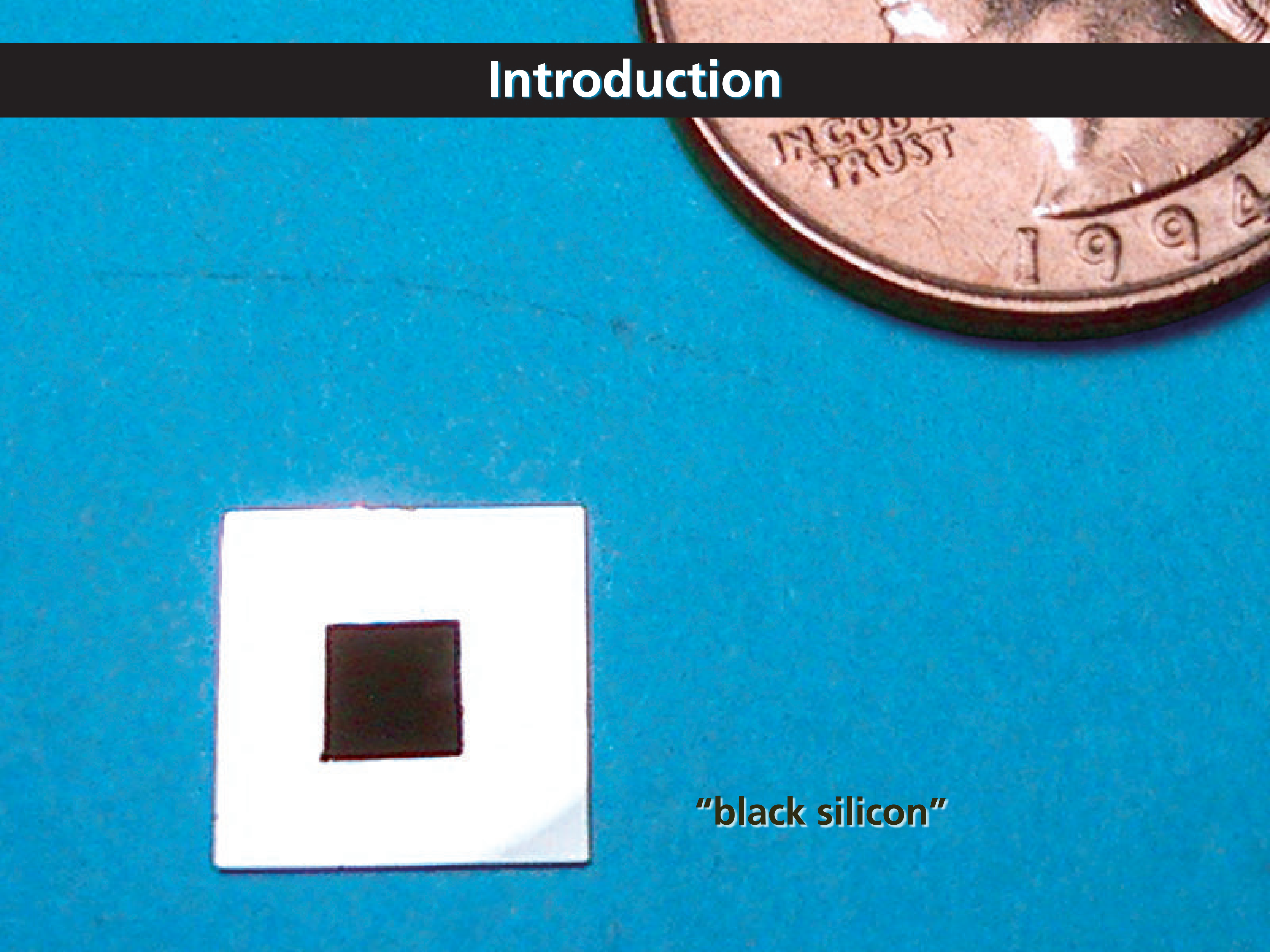


irradiate with 100-fs 10 kJ/m^2 pulses

Introduction

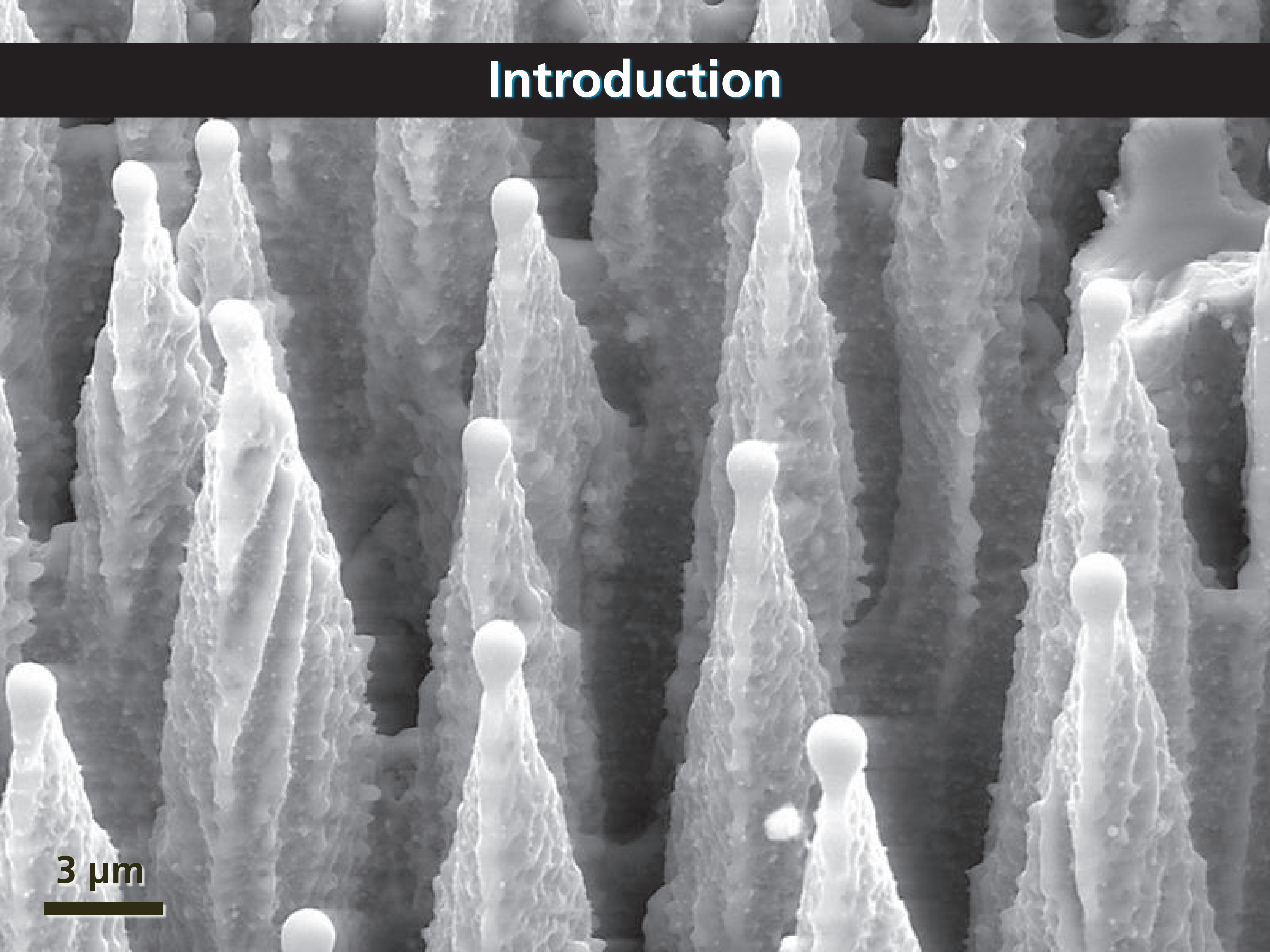


Introduction



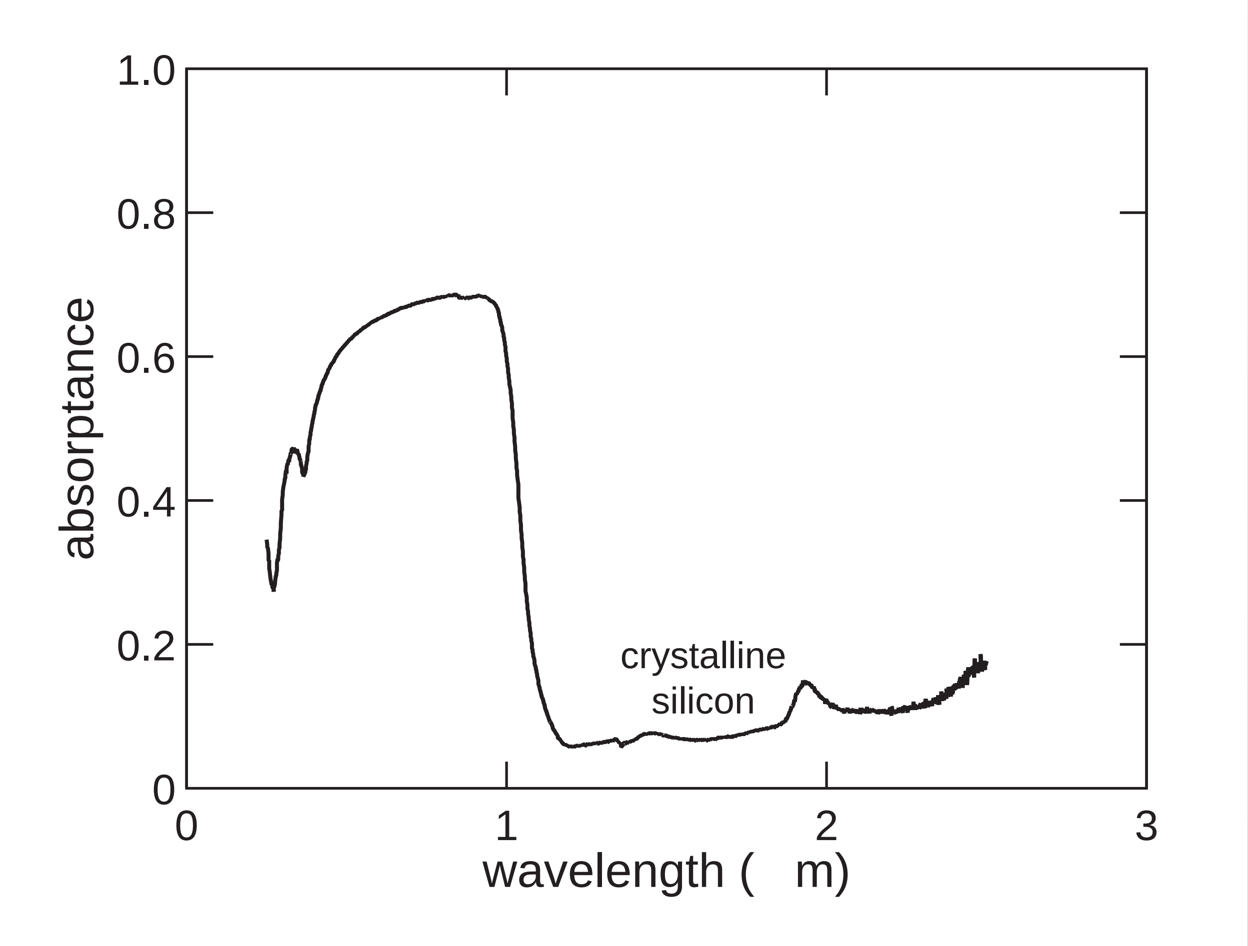
"black silicon"

Introduction



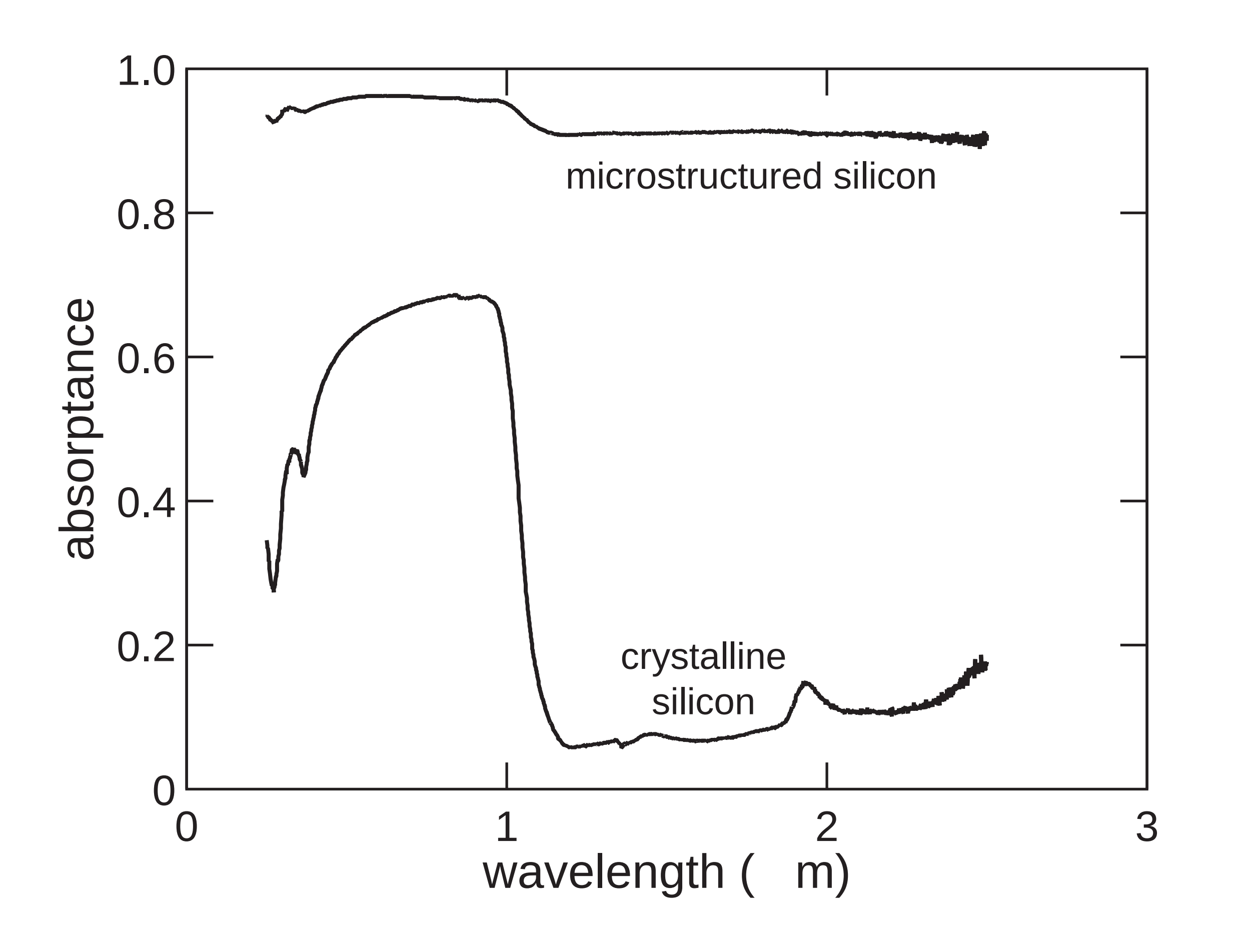
Introduction

absorptance (1 – *R* – *T*)

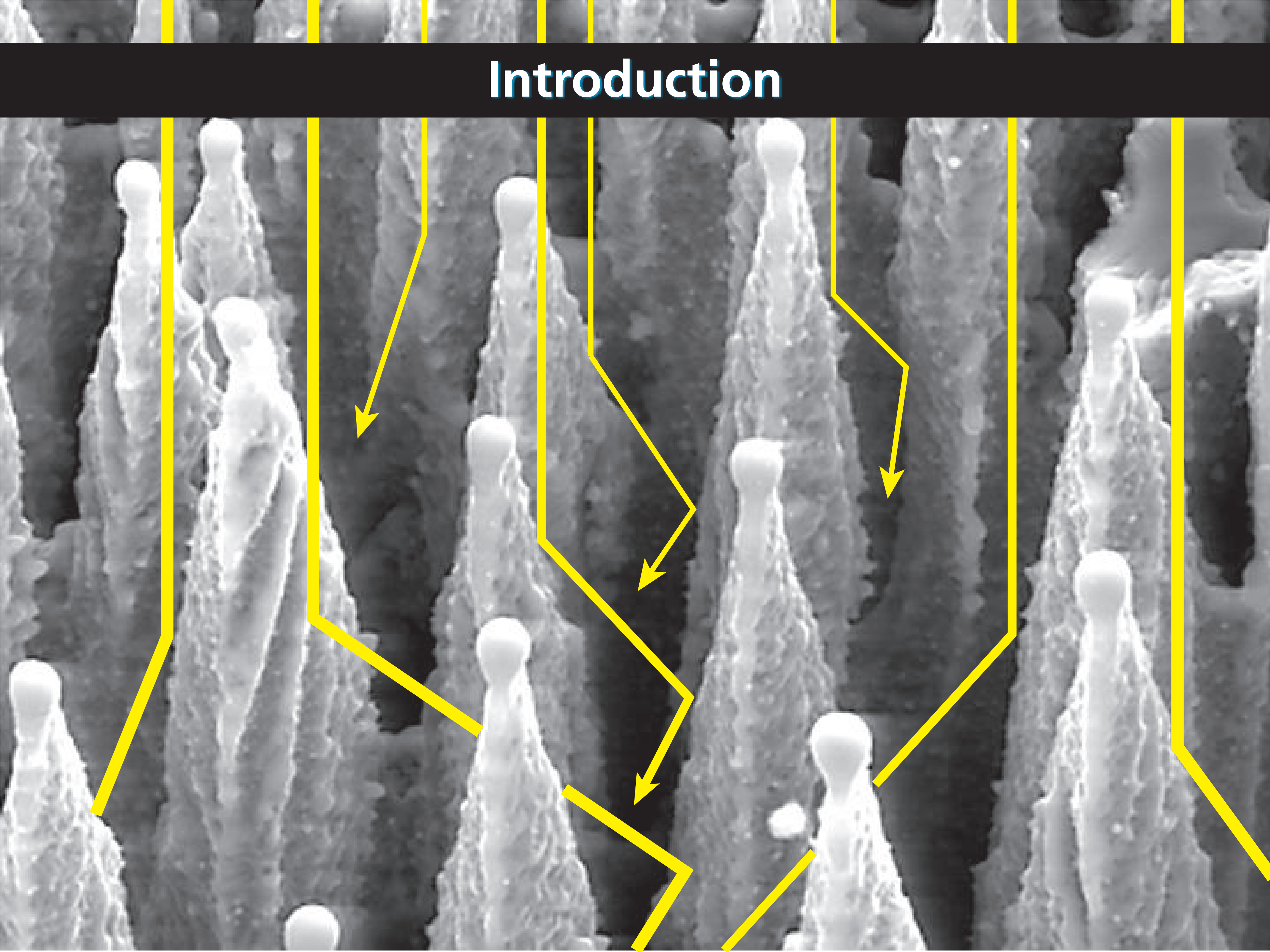


Introduction

absorptance (1 – *R* – *T*)

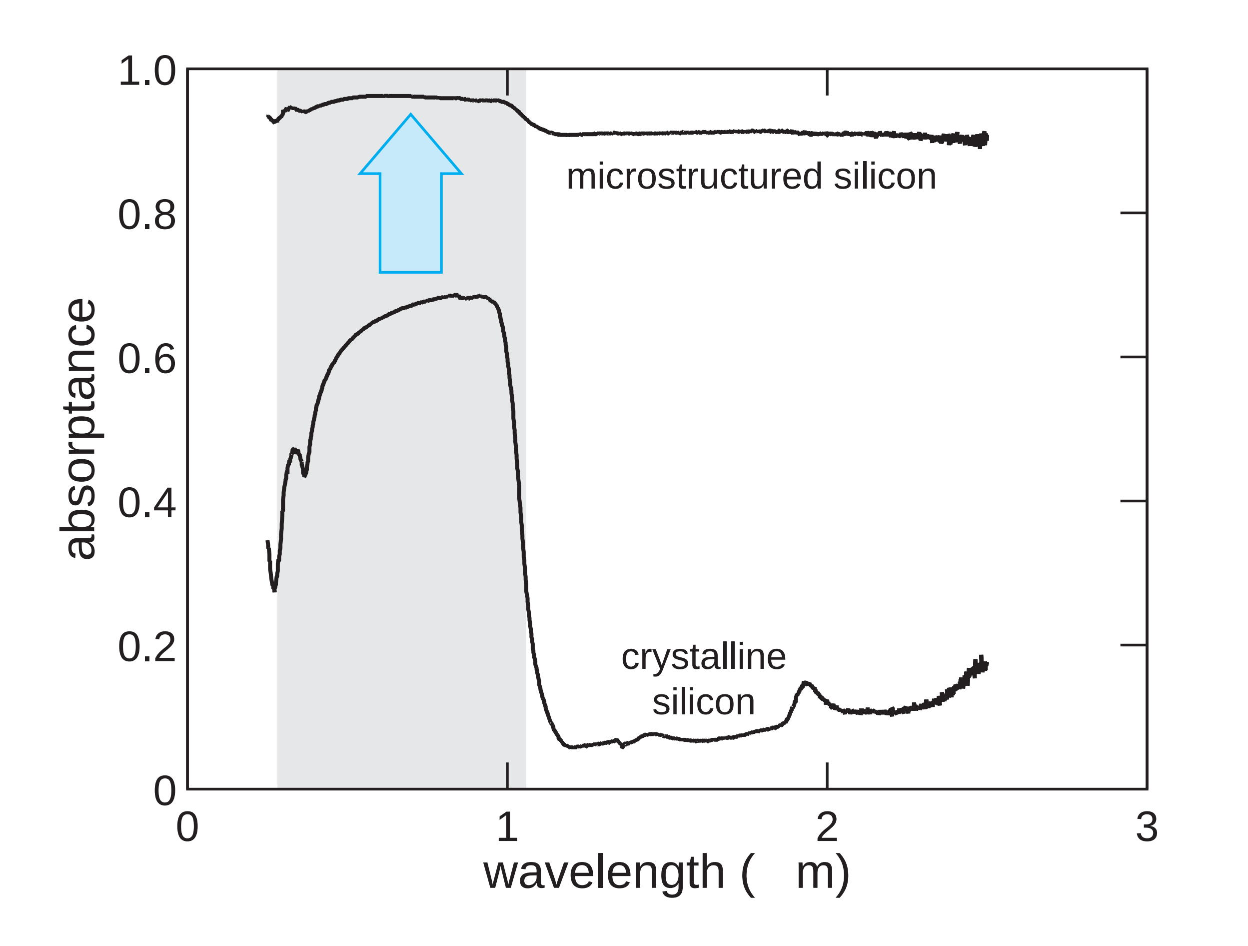


Introduction



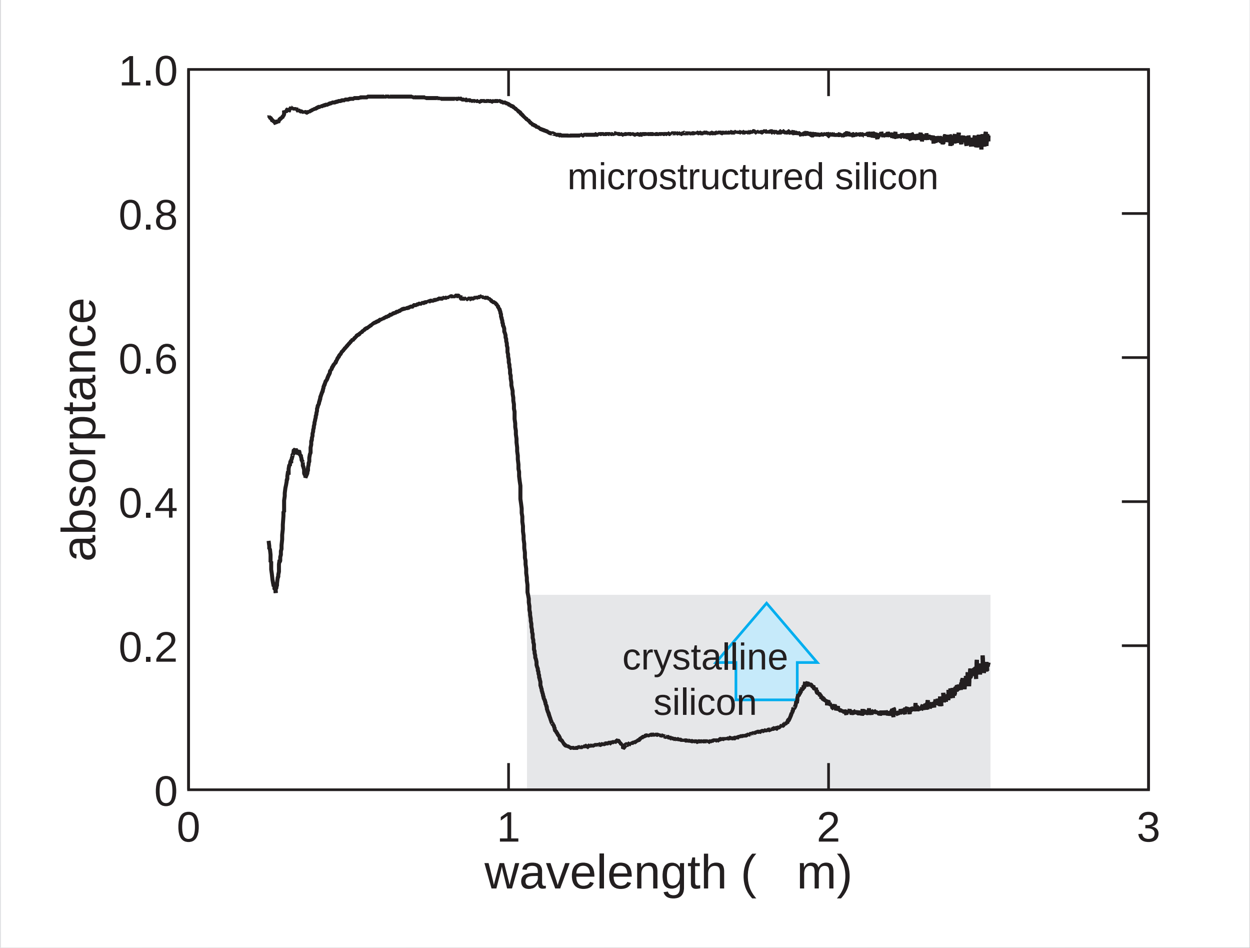
Introduction

multiple reflections enhance absorption



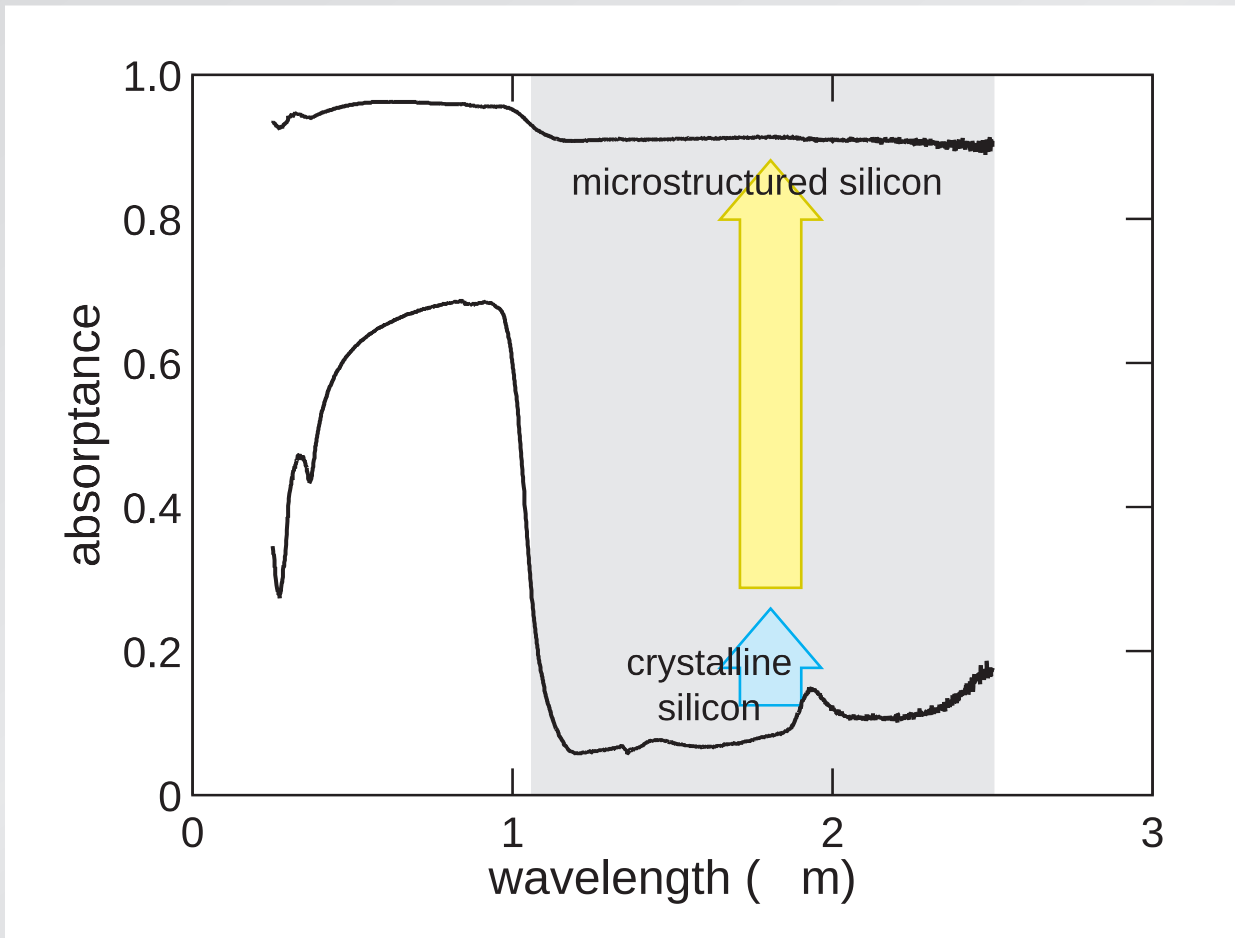
Introduction

multiple reflections enhance absorption



Introduction

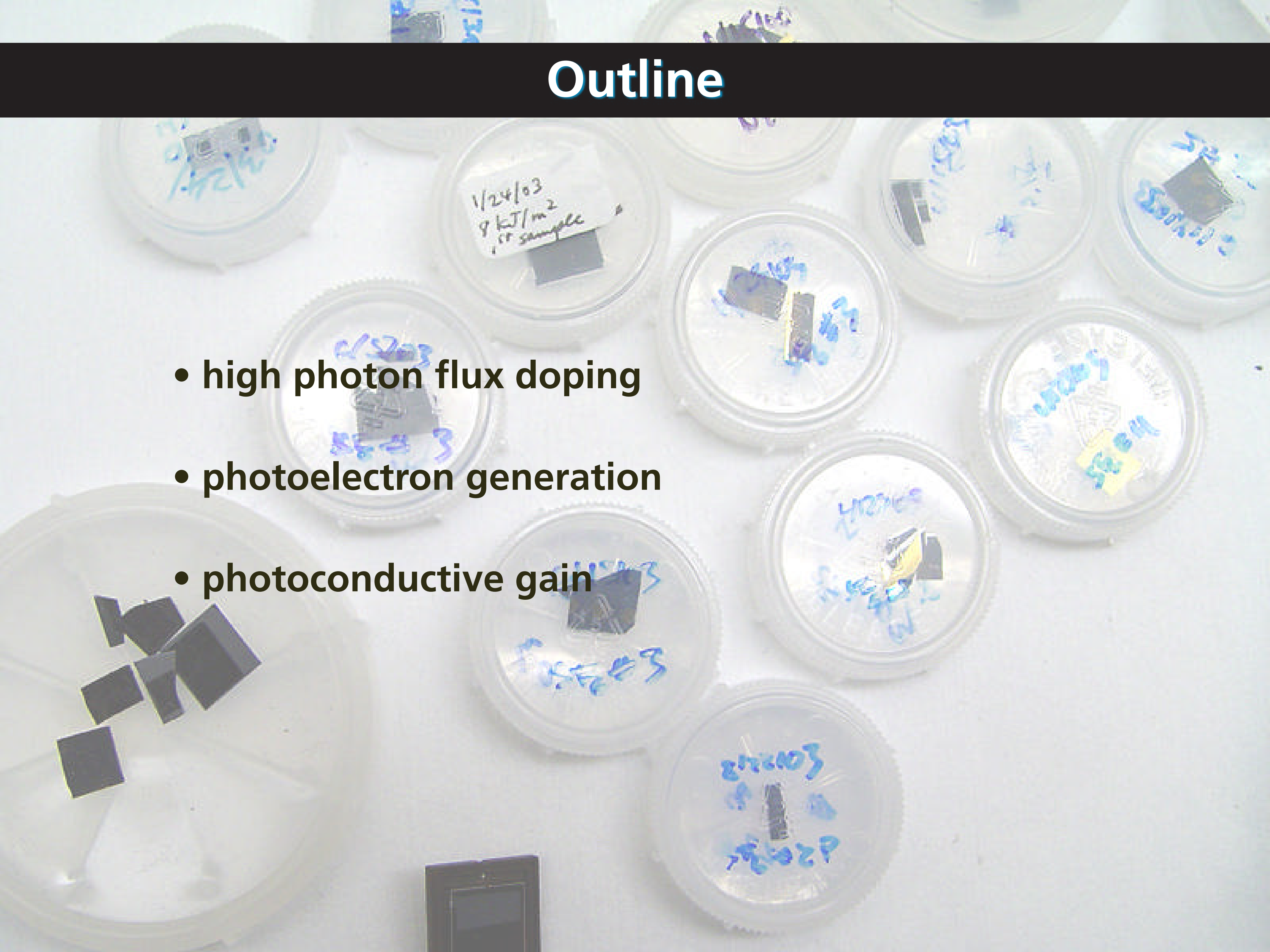
electronic band structure changes



Introduction

band structure changes: defects and/or impurities

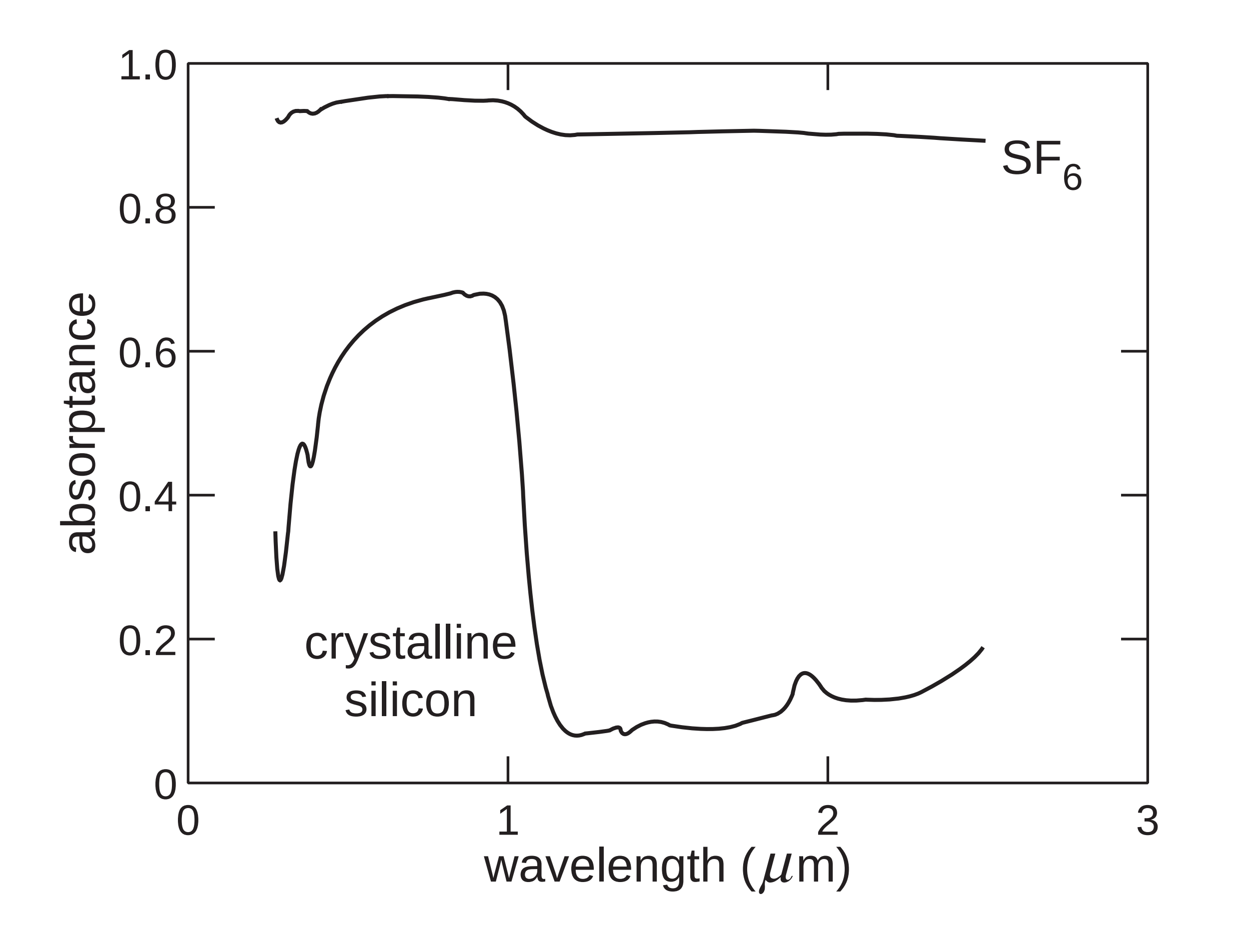
Outline



- high photon flux doping
- photoelectron generation
- photoconductive gain

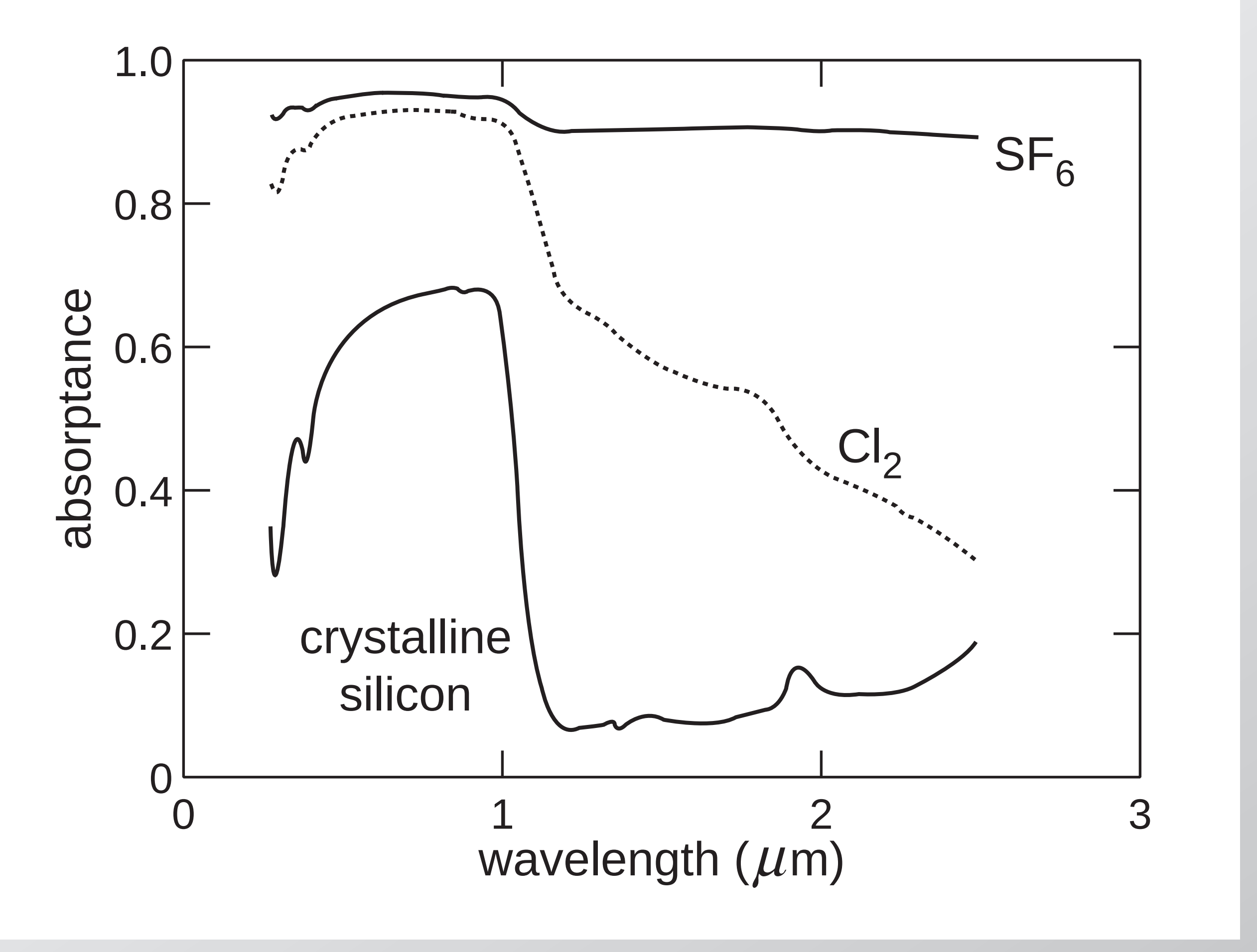
High photon flux doping

microstructure with different gases



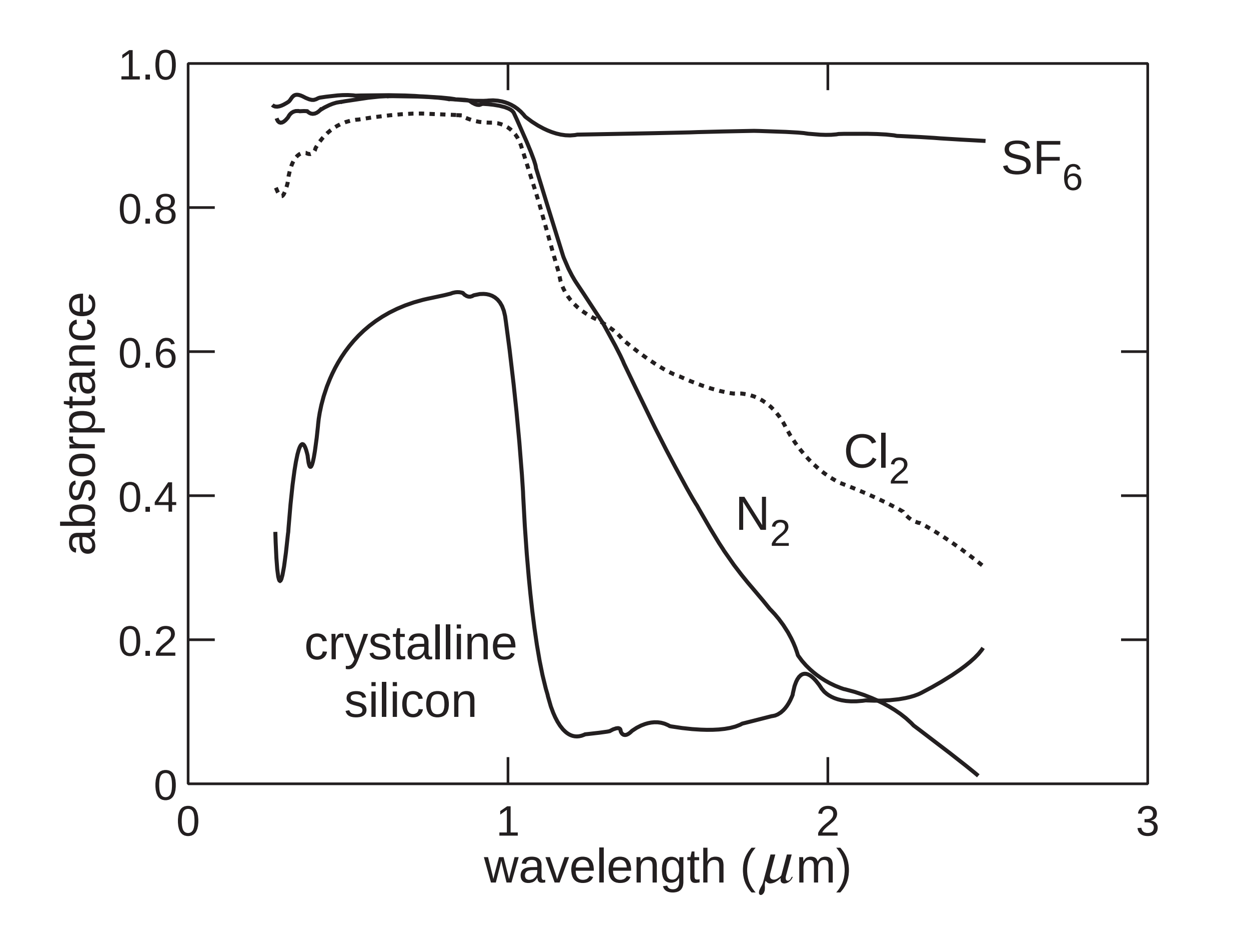
High photon flux doping

microstructure with different gases



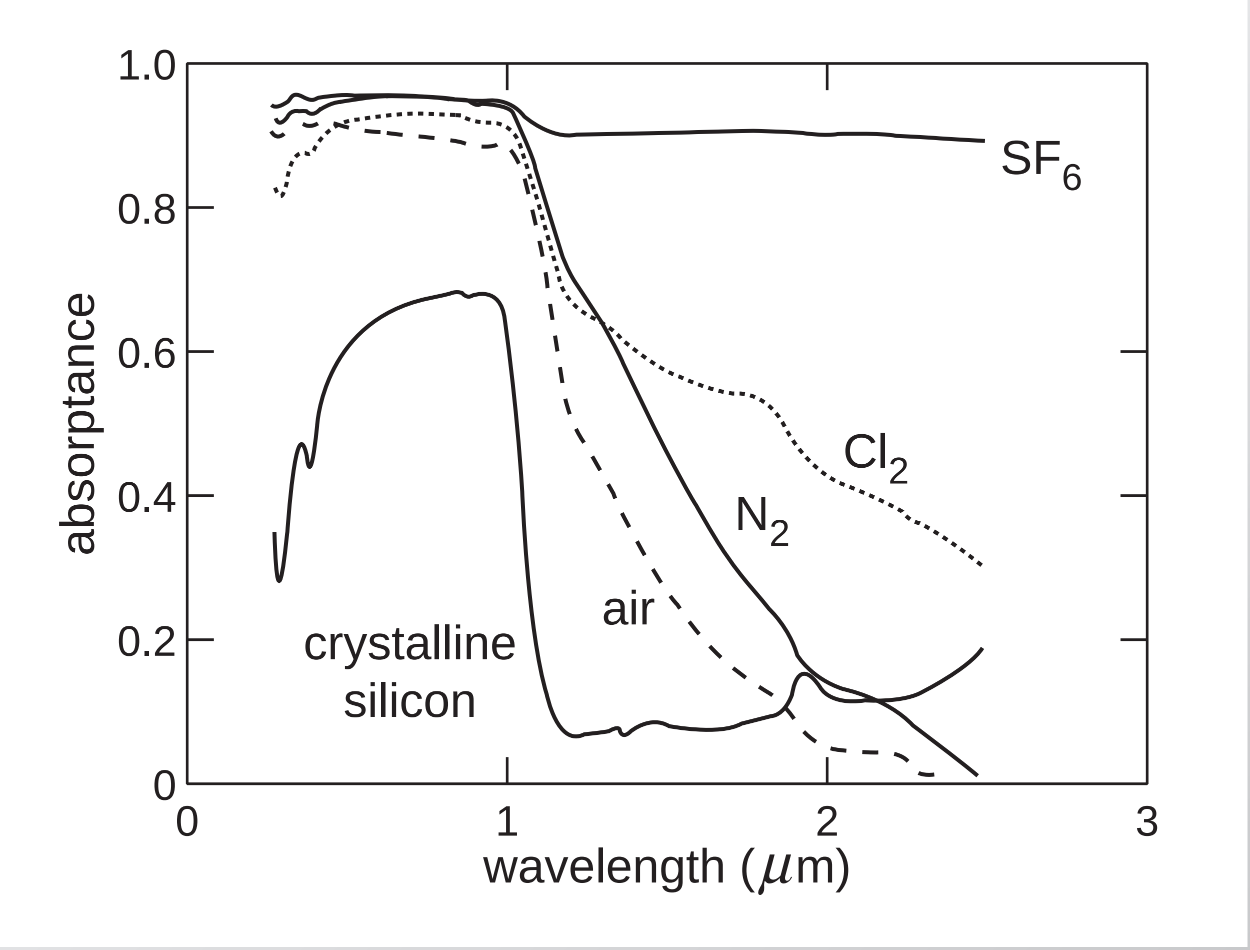
High photon flux doping

microstructure with different gases



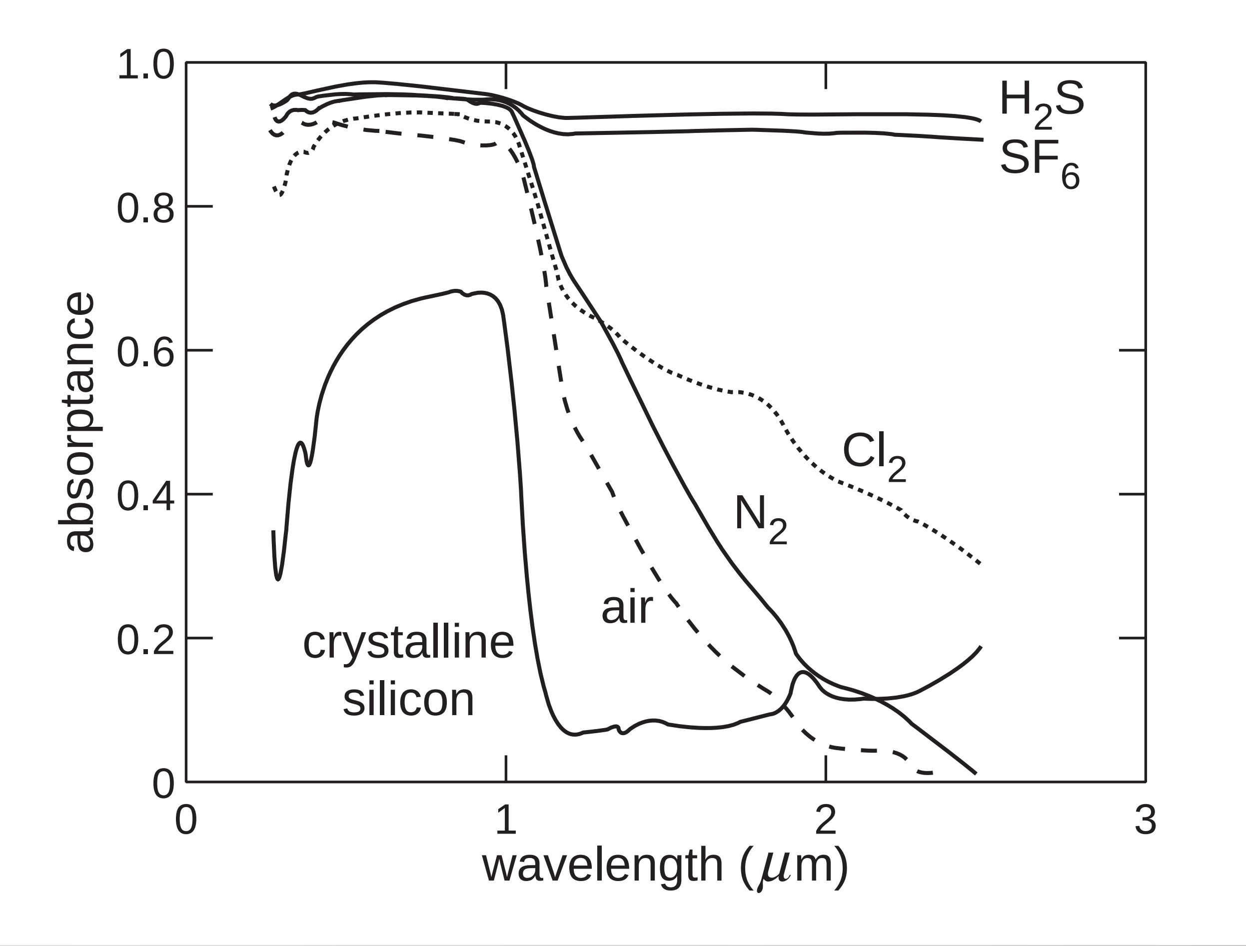
High photon flux doping

microstructure with different gases



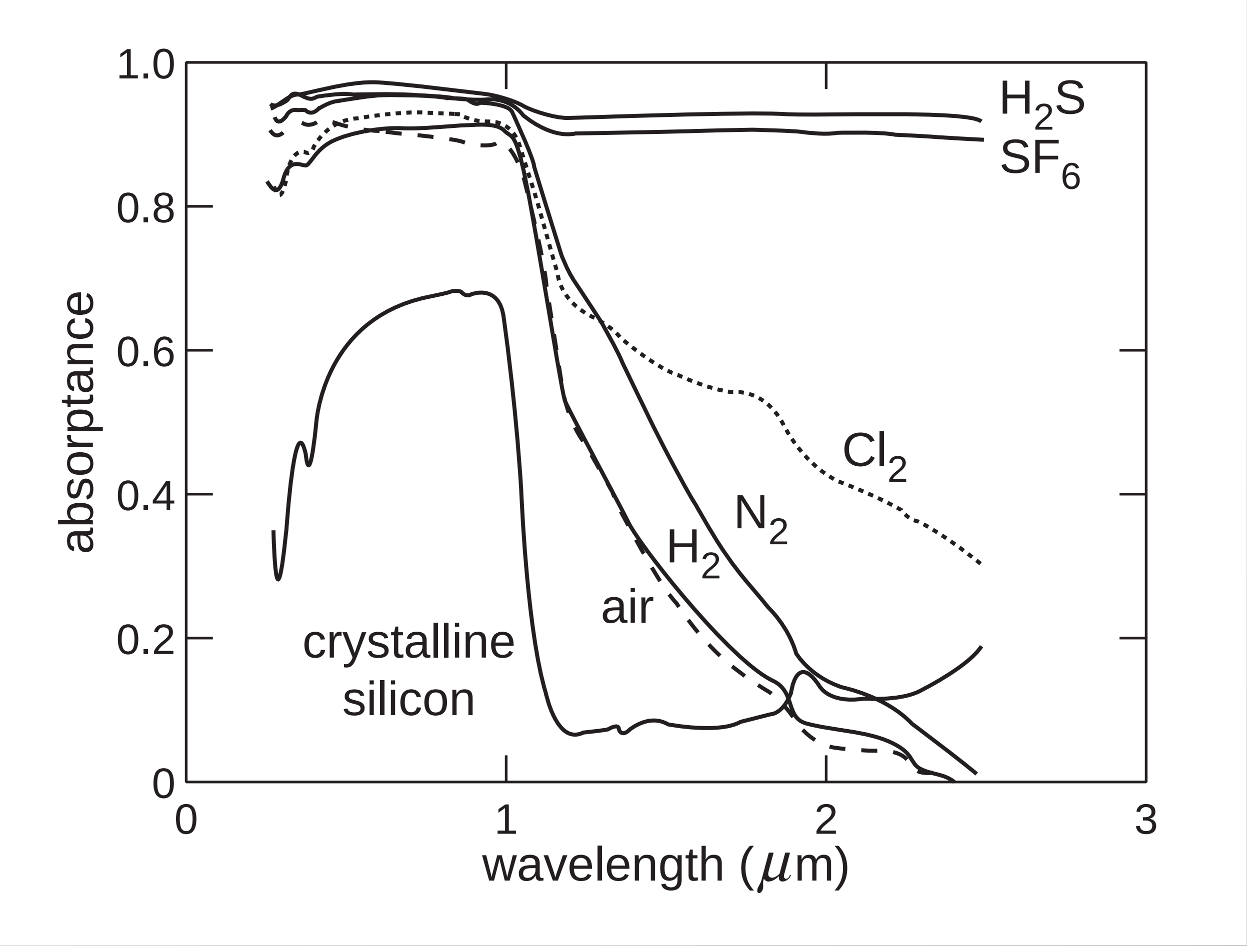
High photon flux doping

microstructure with different gases



High photon flux doping

microstructure with different gases

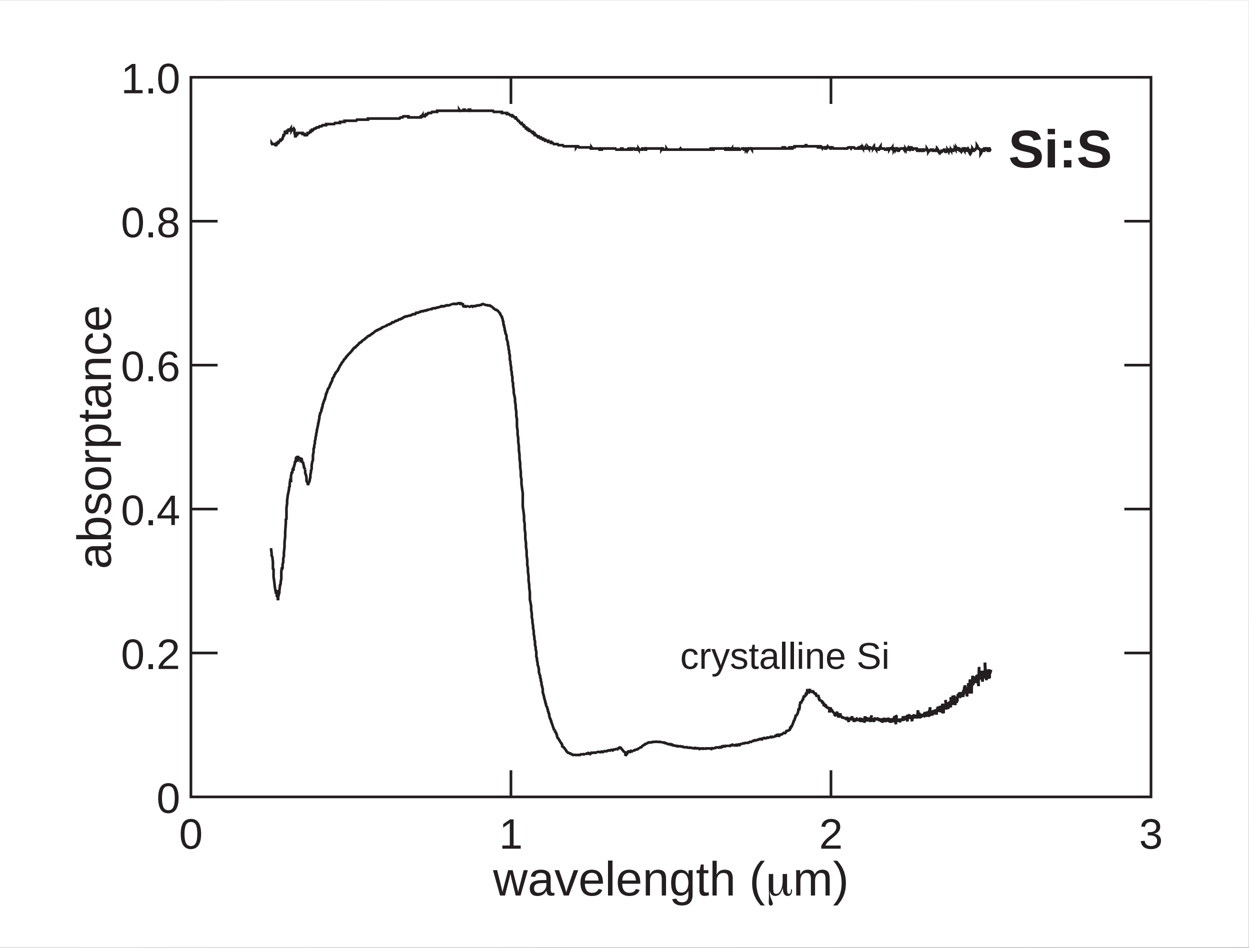


Introduction

sulfur required for below band gap absorption

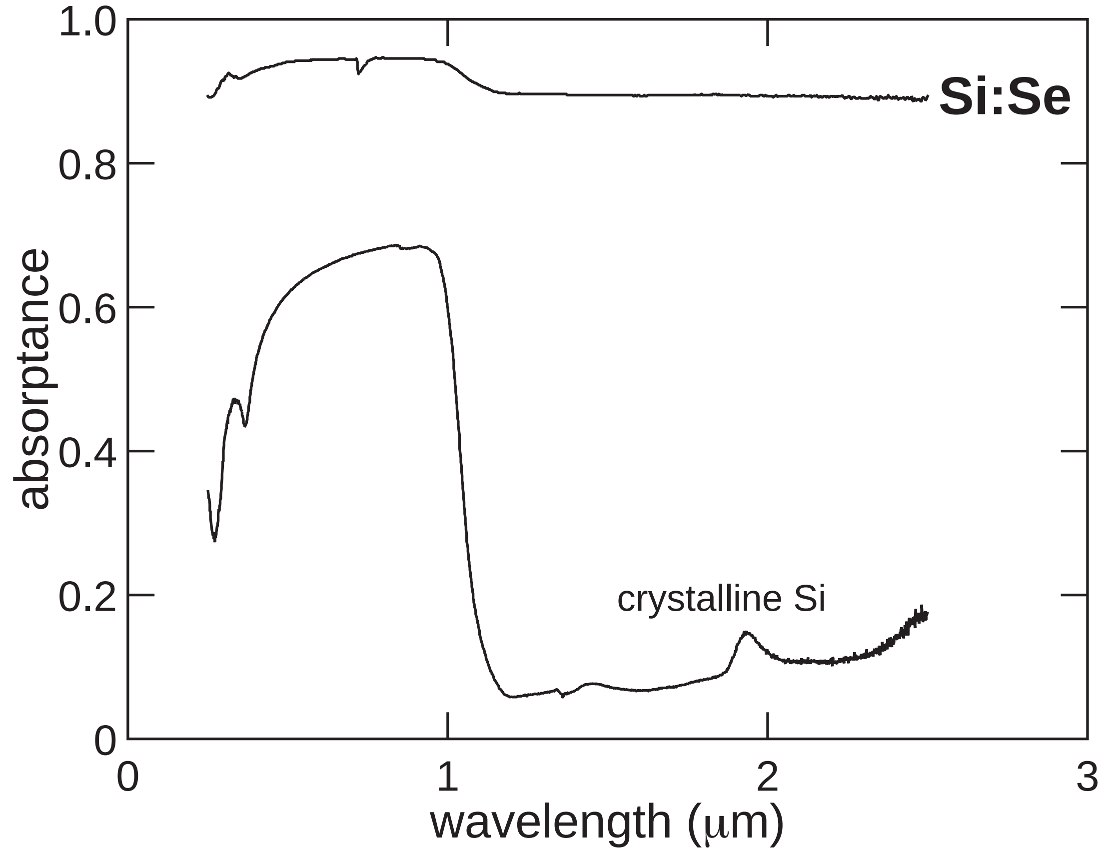
High photon flux doping

other chalcogens yield similar results



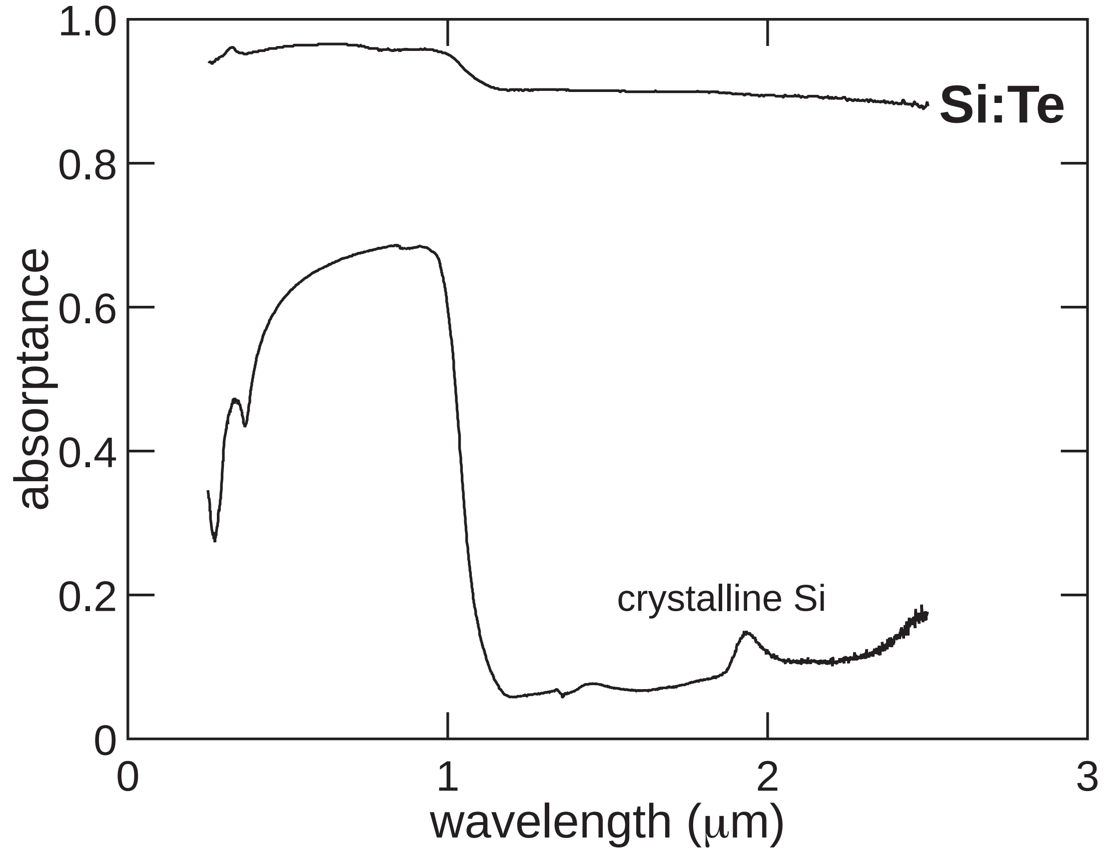
High photon flux doping

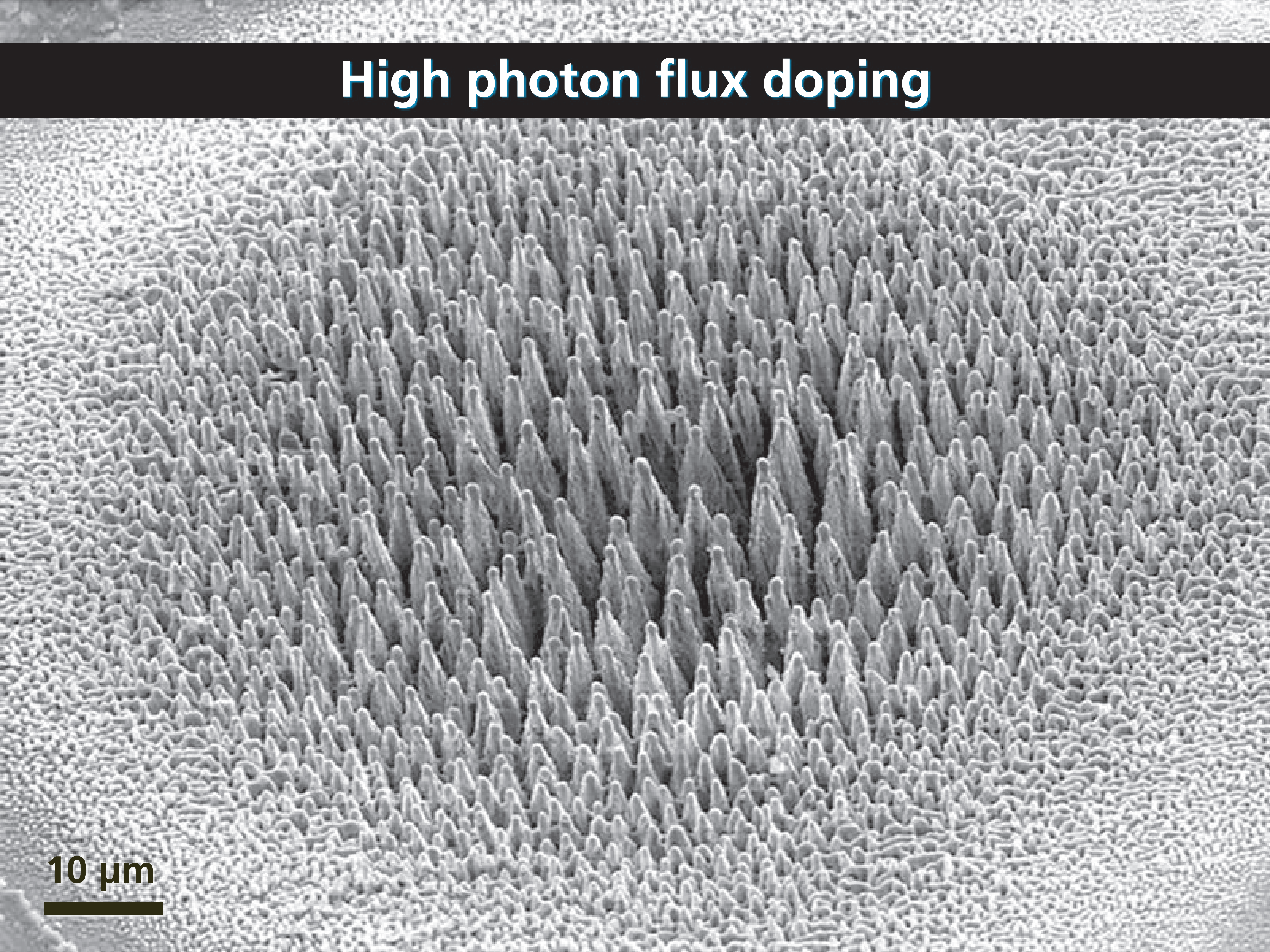
other chalcogens yield similar results

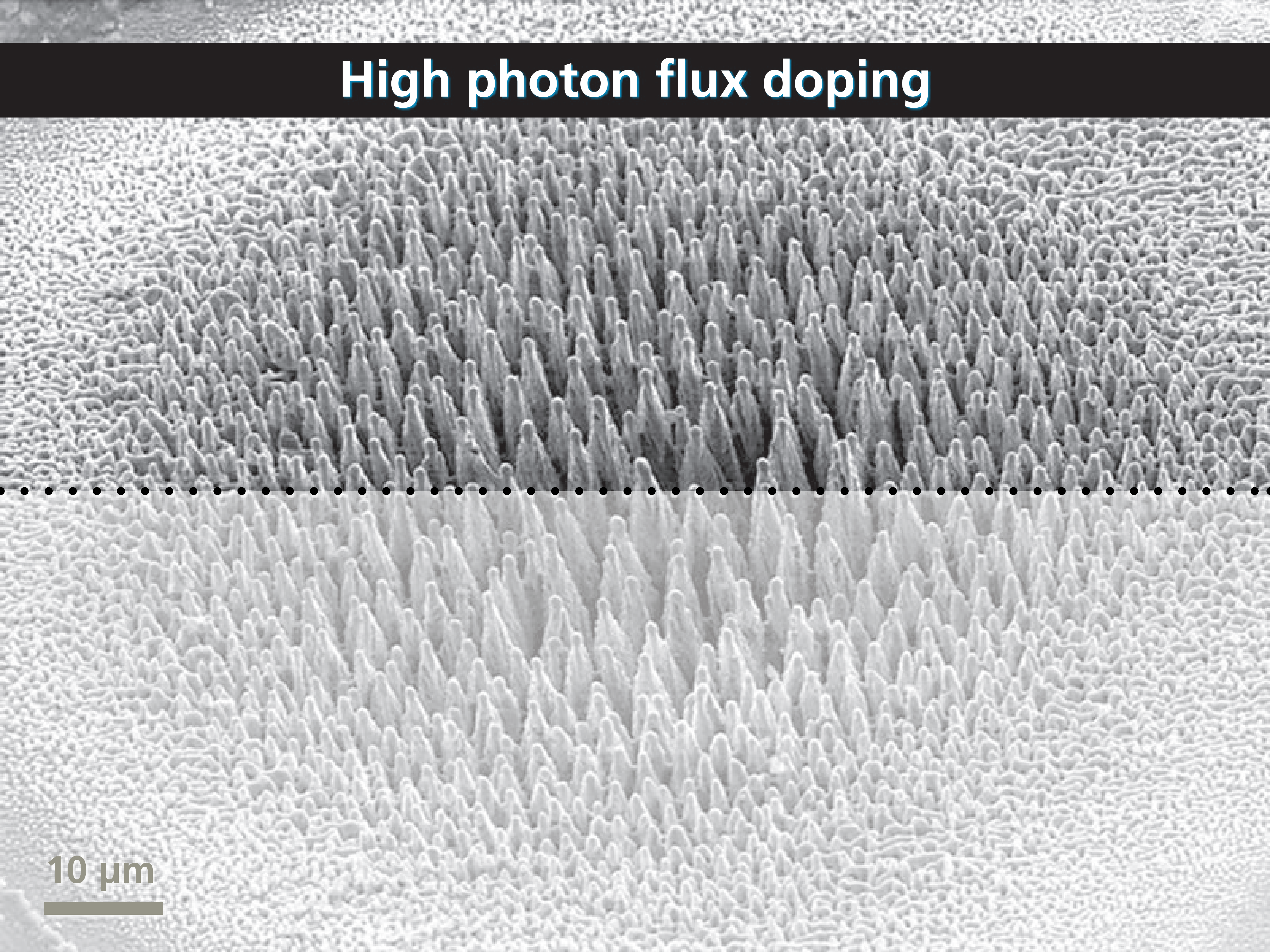


High photon flux doping

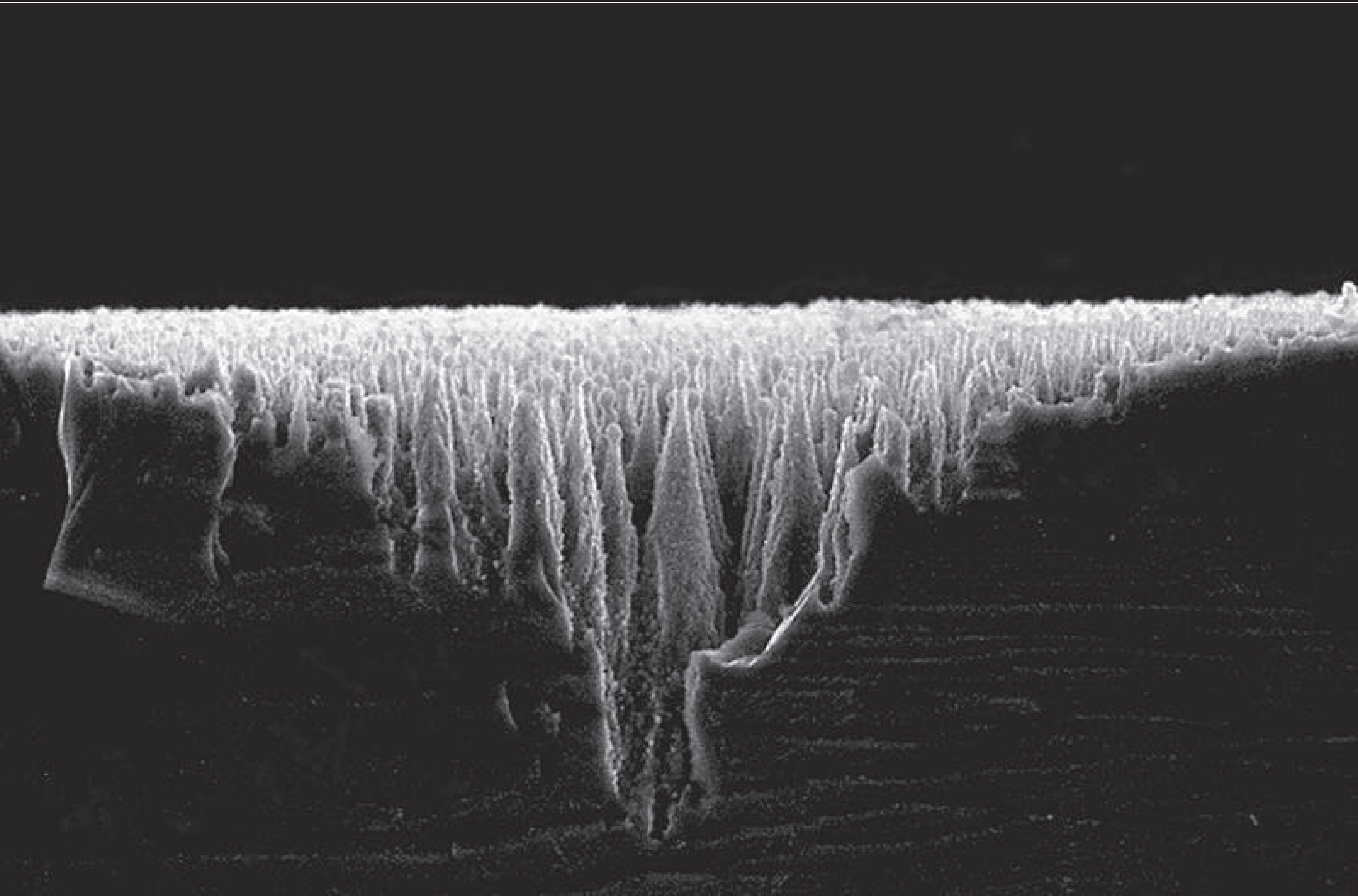
other chalcogens yield similar results



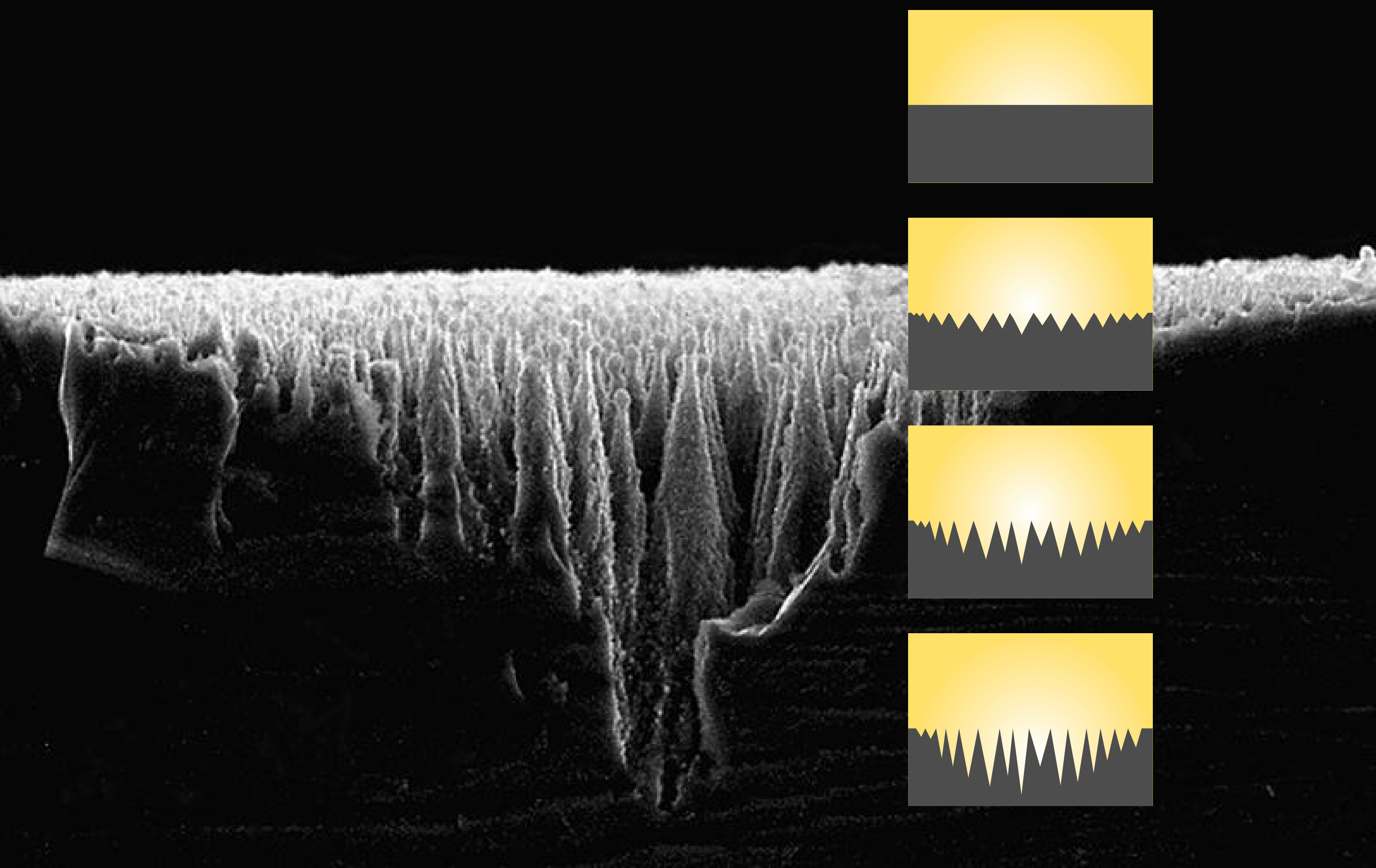

High photon flux doping
10 μm


High photon flux doping
10 µm

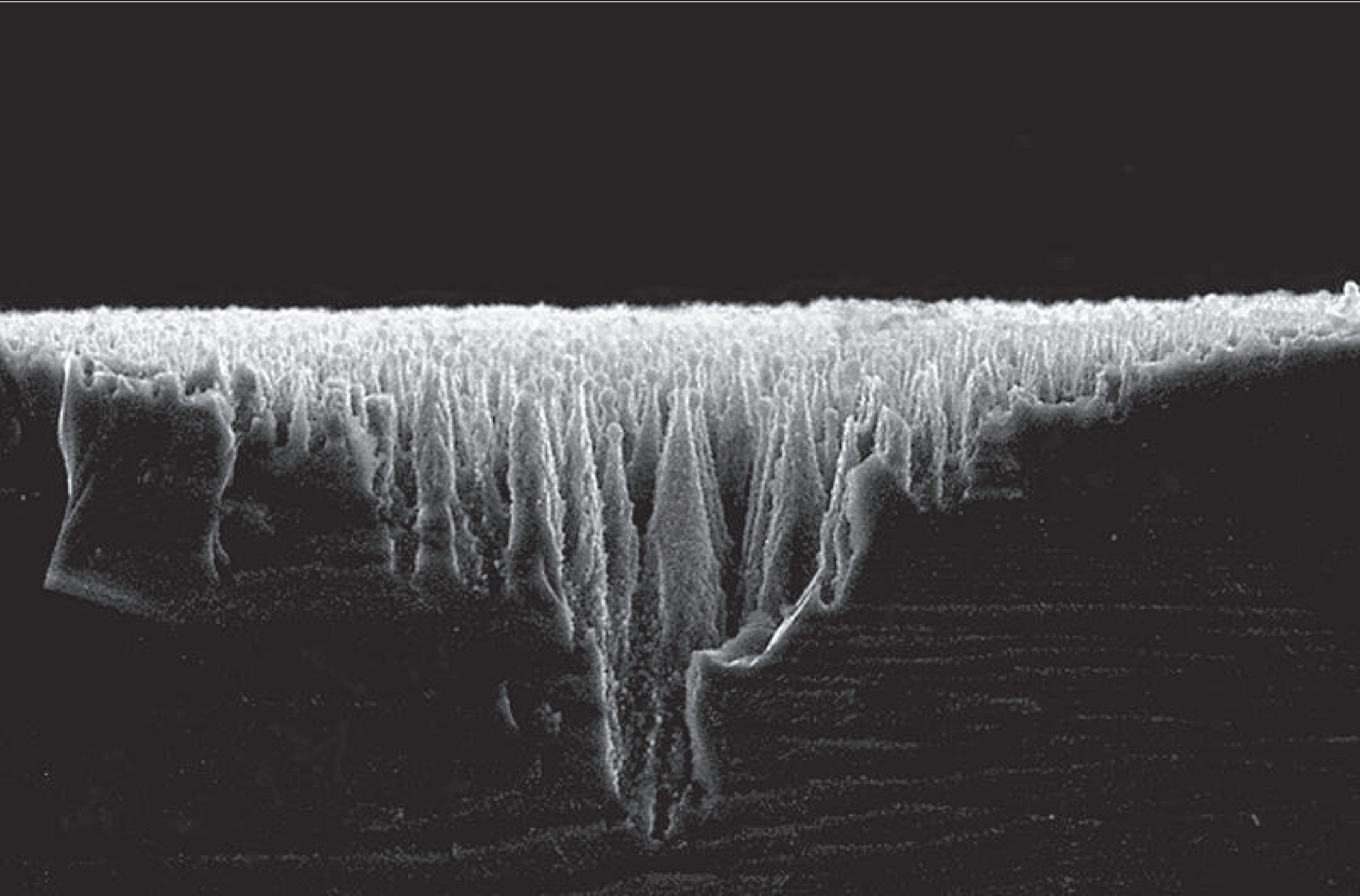
High photon flux doping



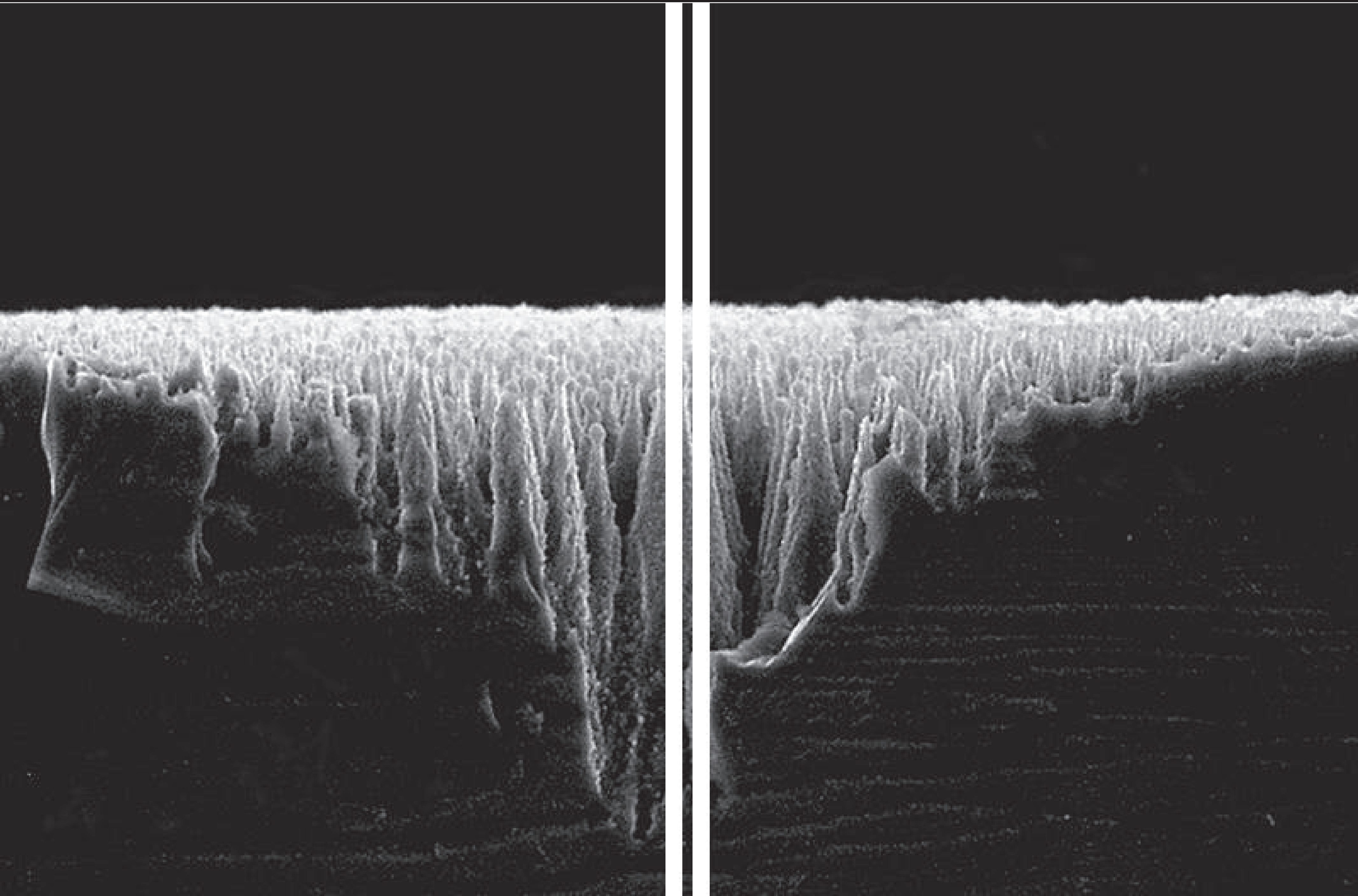
High photon flux doping



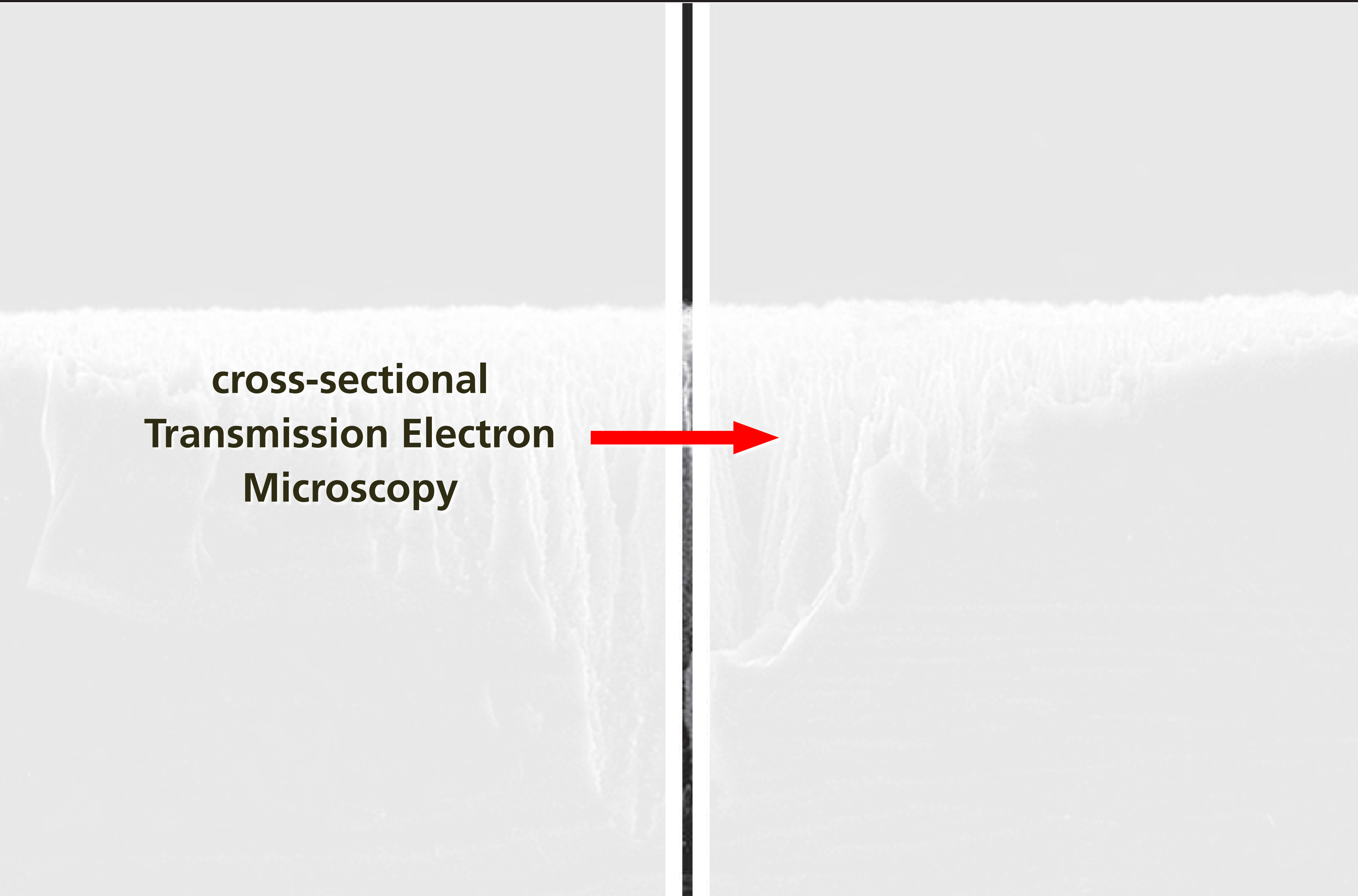
High photon flux doping



High photon flux doping

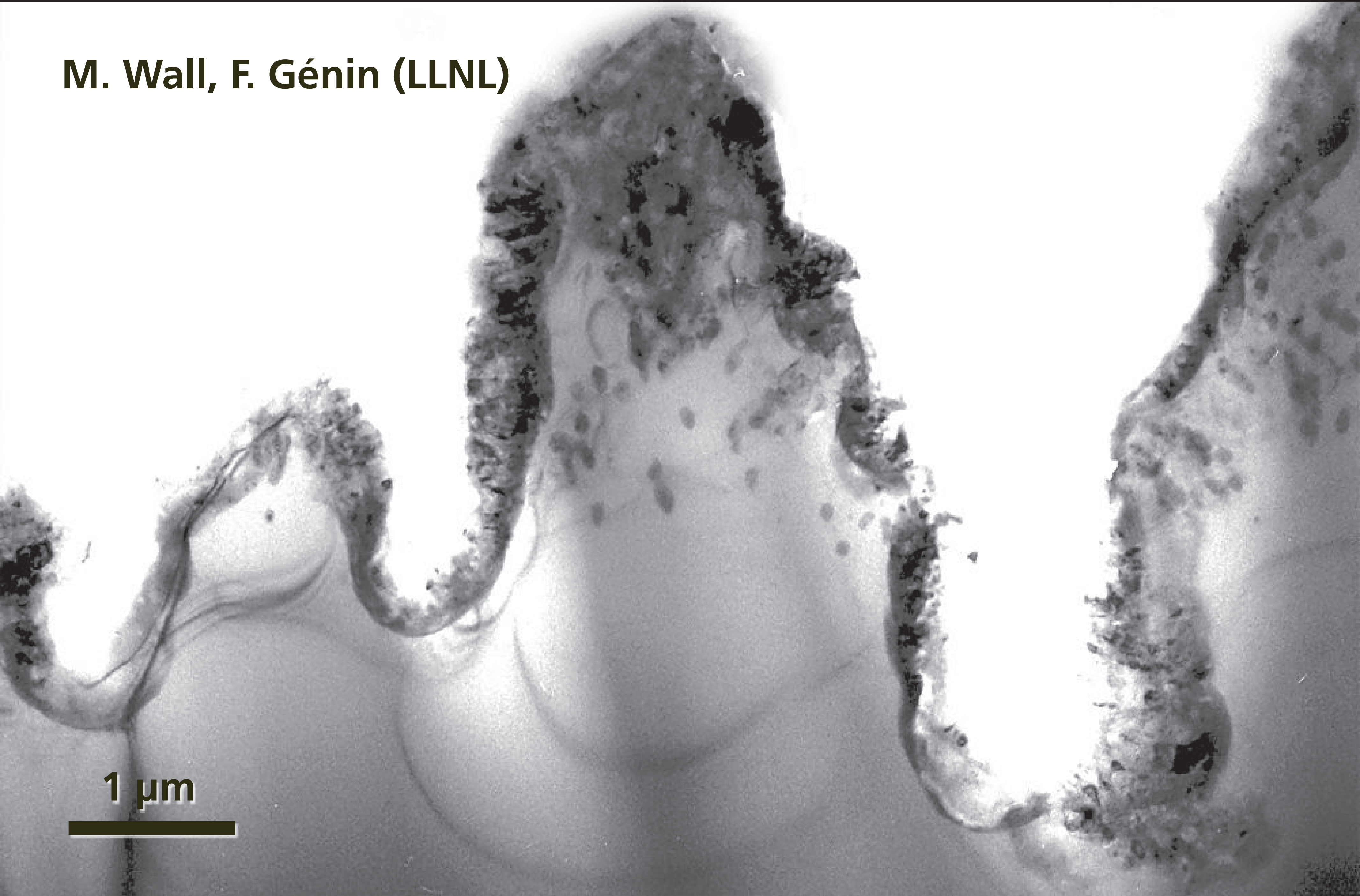


High photon flux doping

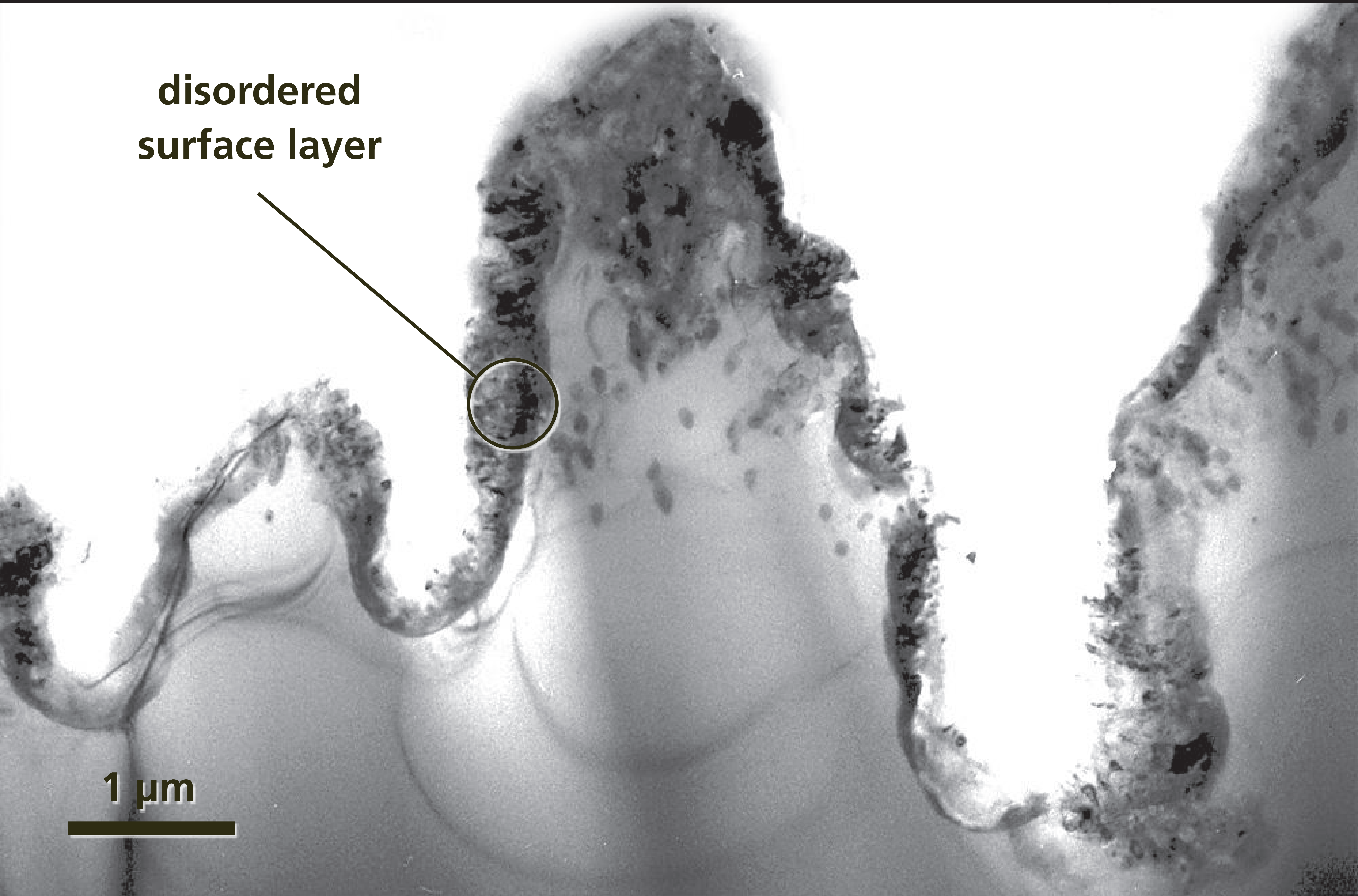


High photon flux doping

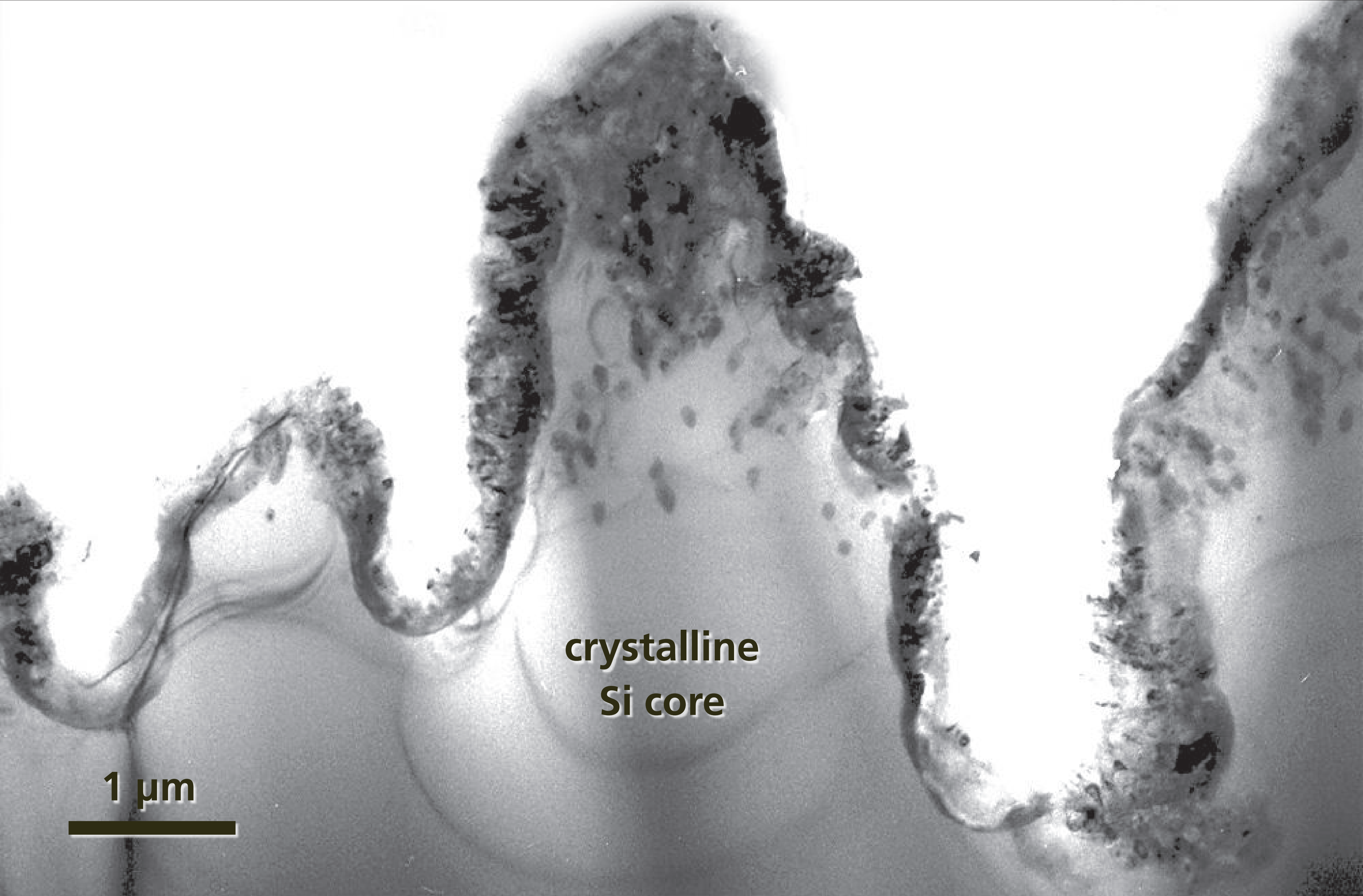
M. Wall, F. Génin (LLNL)



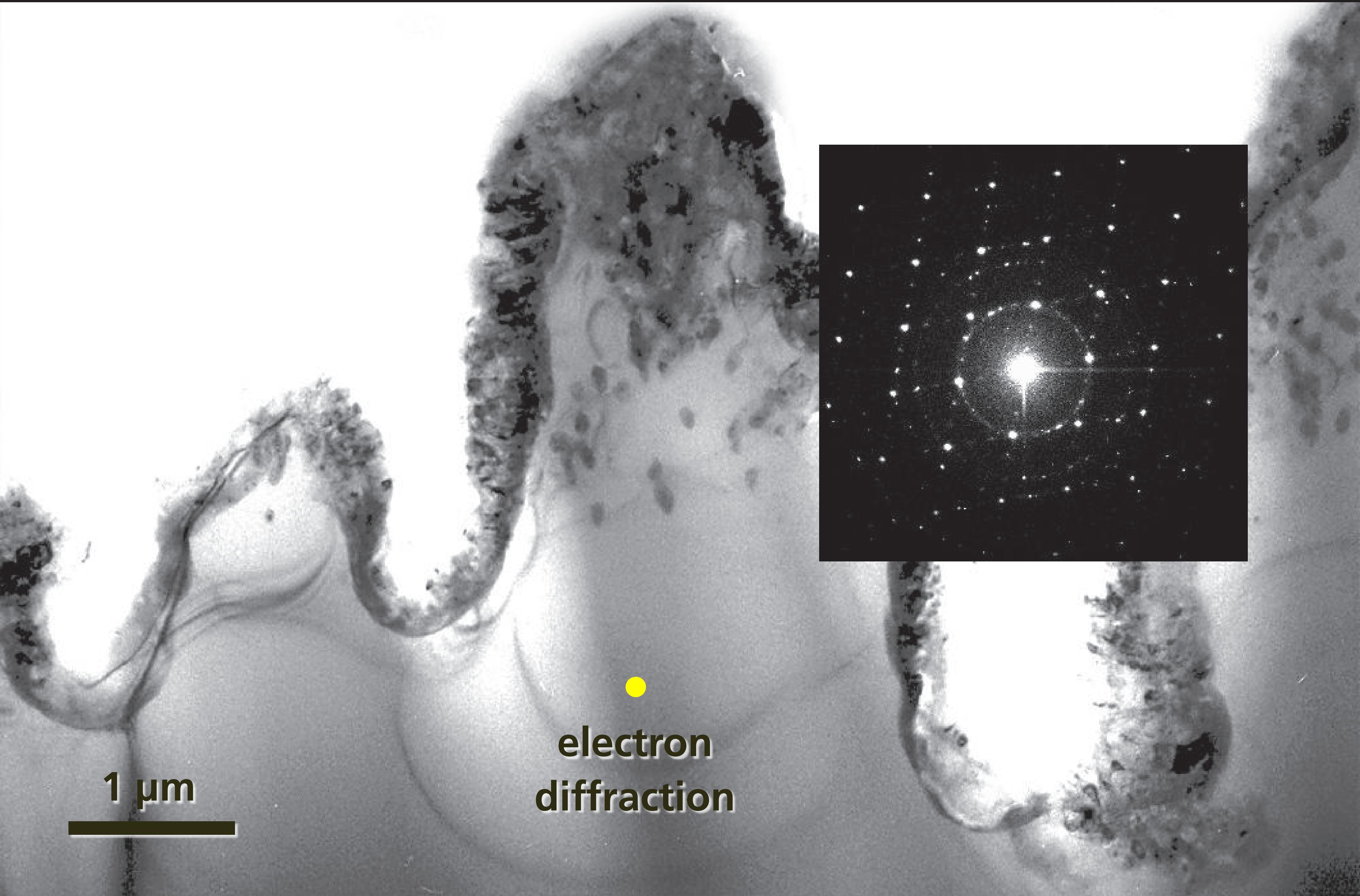
High photon flux doping



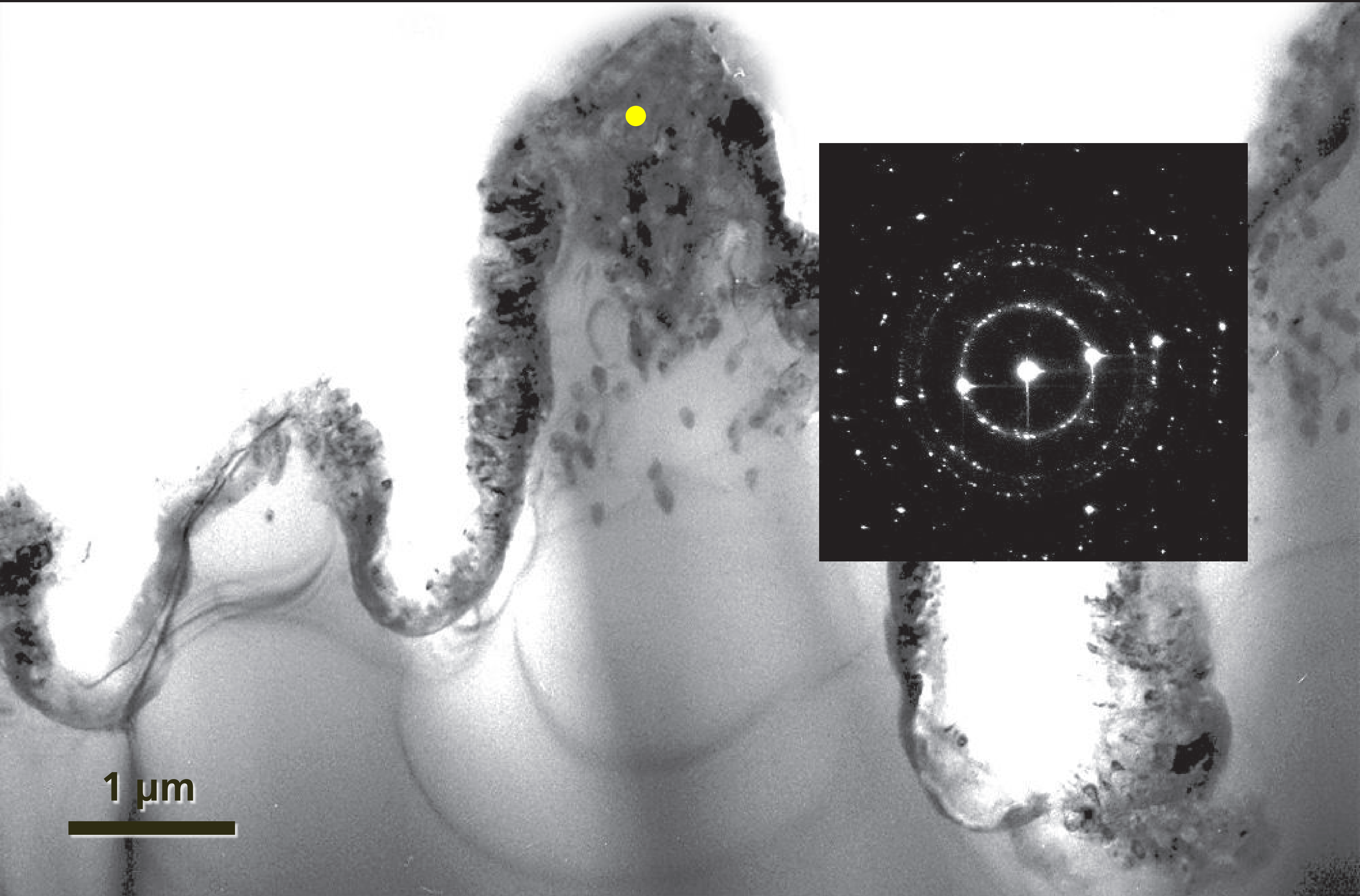
High photon flux doping



High photon flux doping

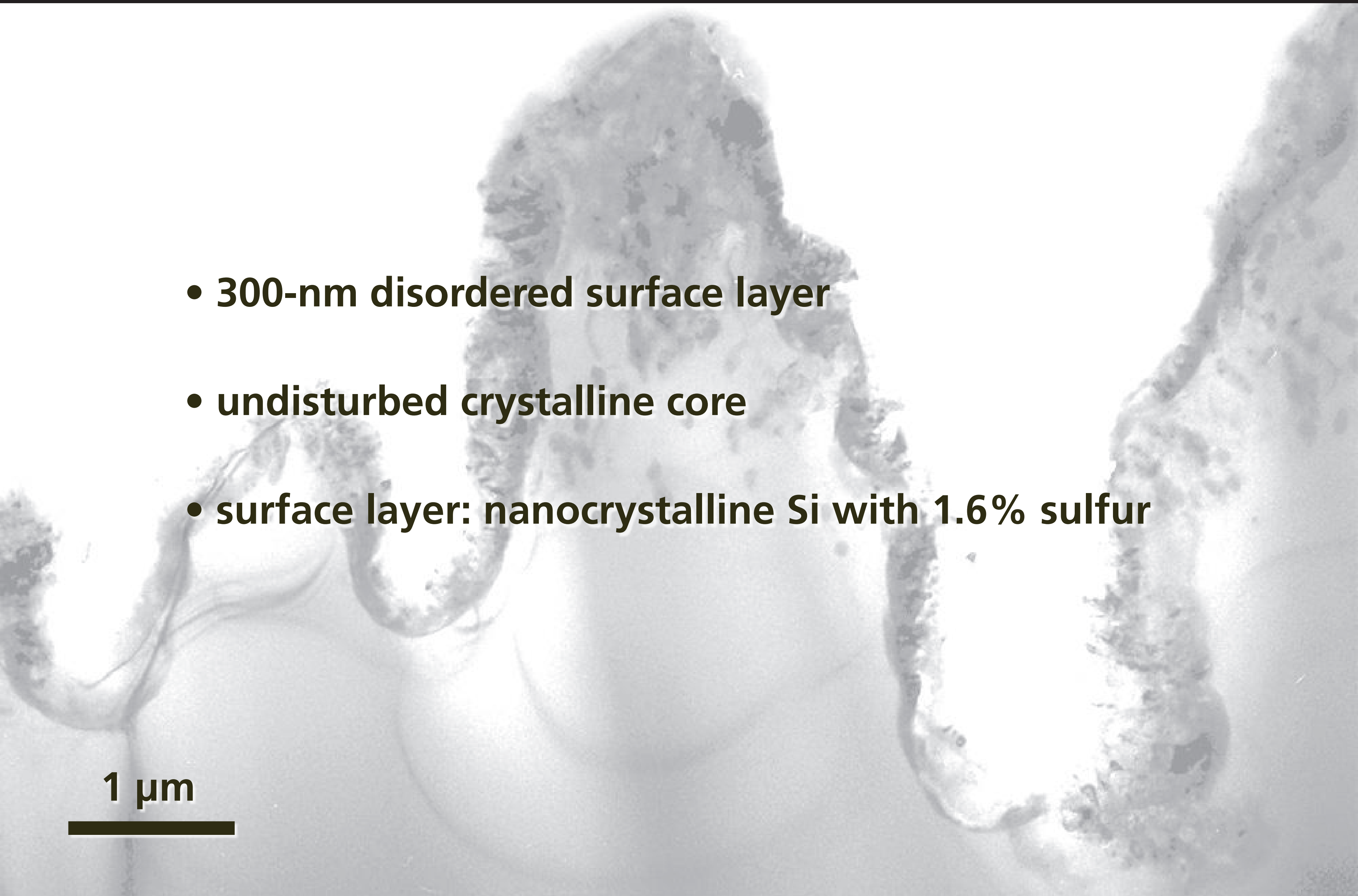


High photon flux doping



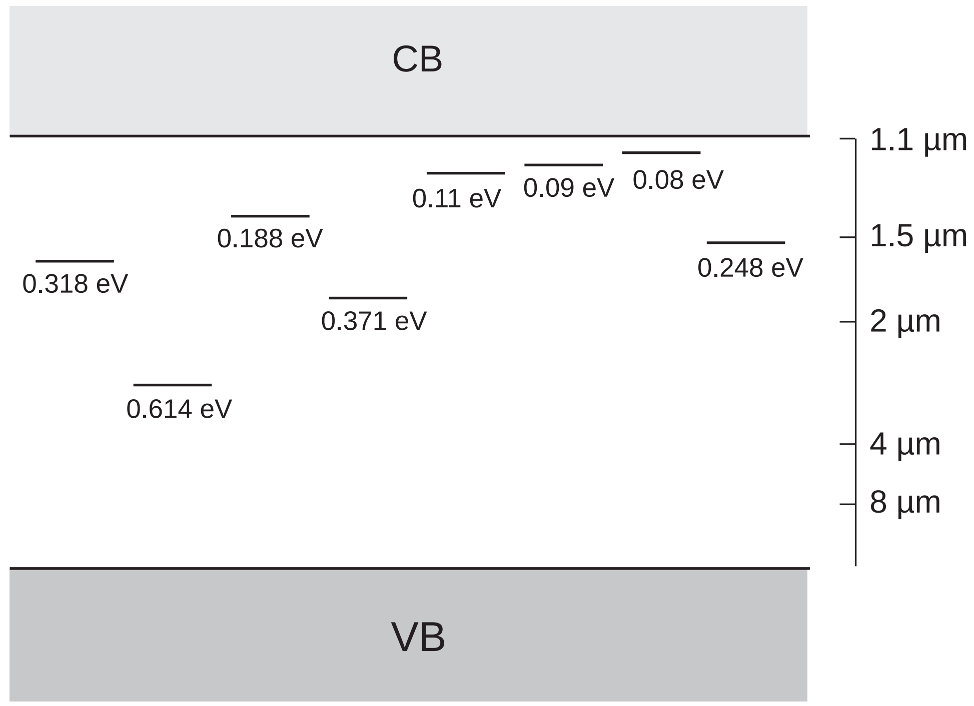
High photon flux doping

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



High photon flux doping

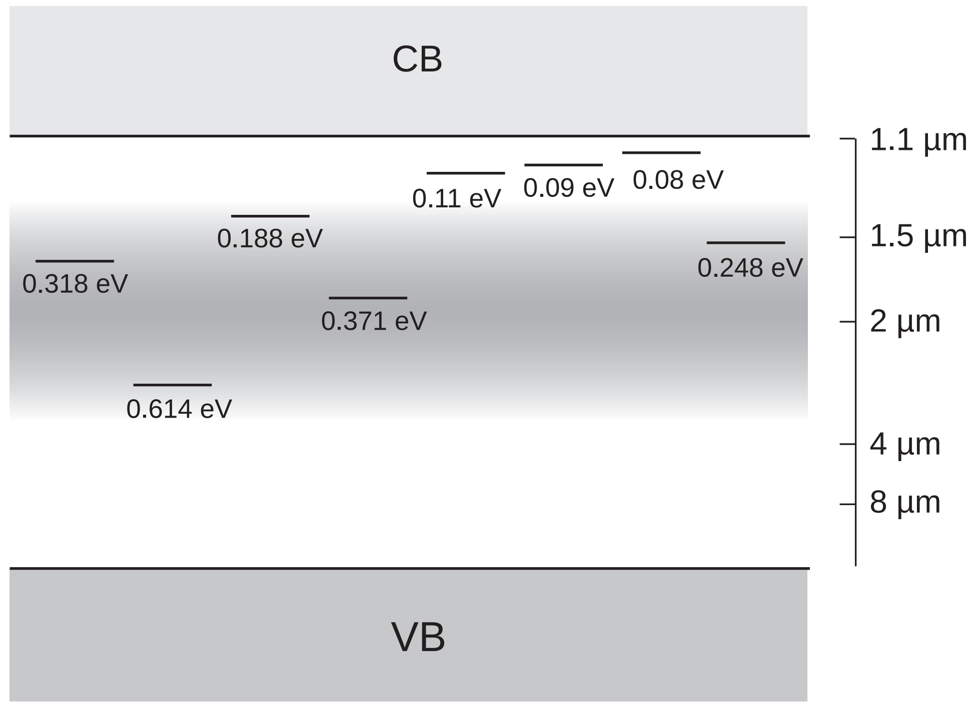
1 part in 10^6 sulfur introduces states in gap



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

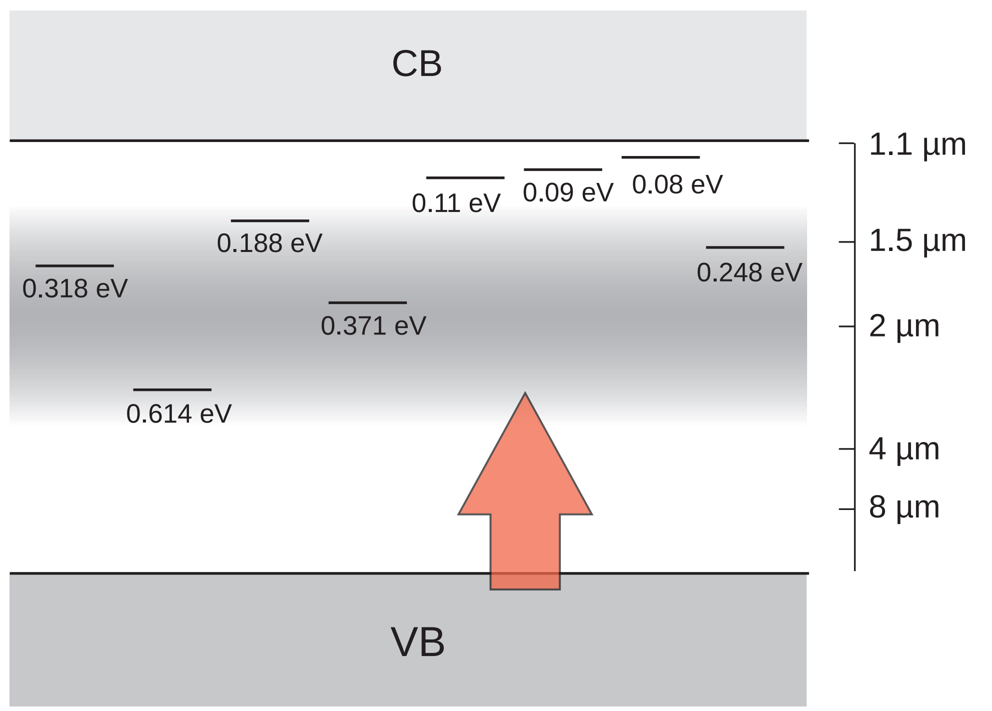
High photon flux doping

at high concentration states broaden into band



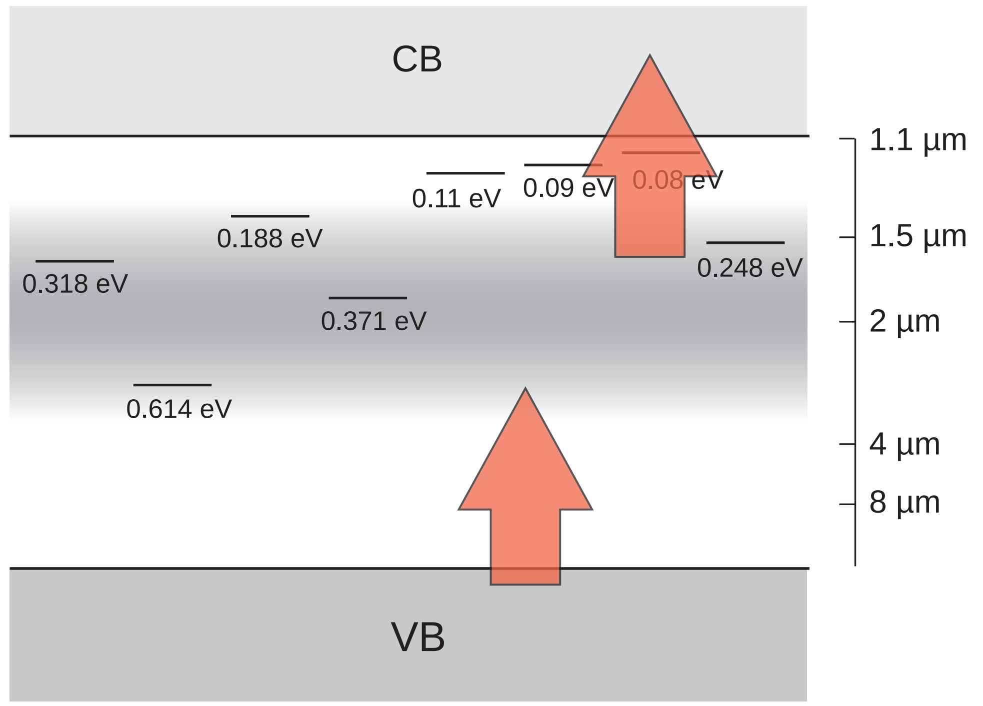
High photon flux doping

absorption extends into infrared



High photon flux doping

donor or acceptor states, depending on Fermi level

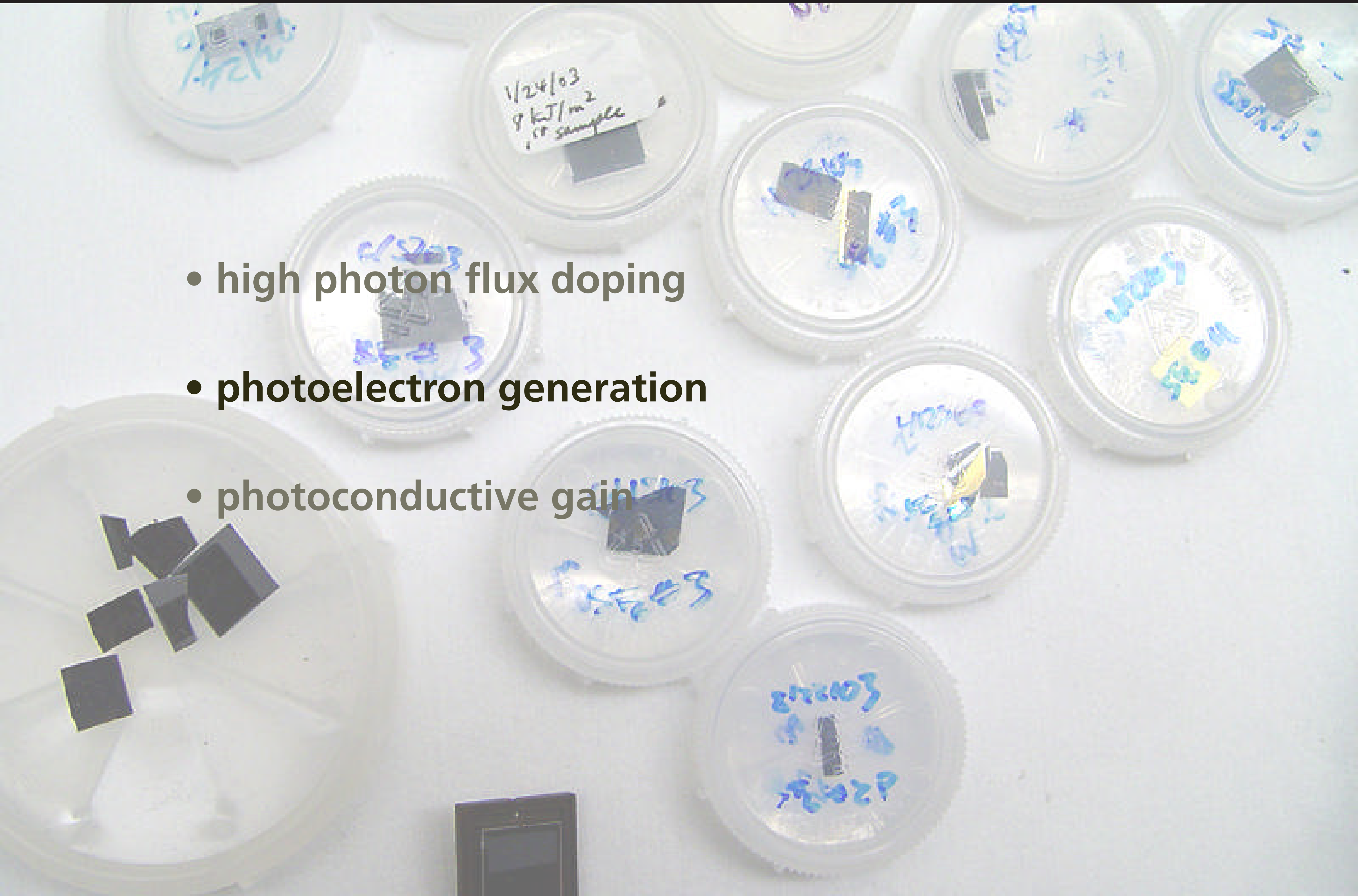


High photon flux doping

Things to keep in mind

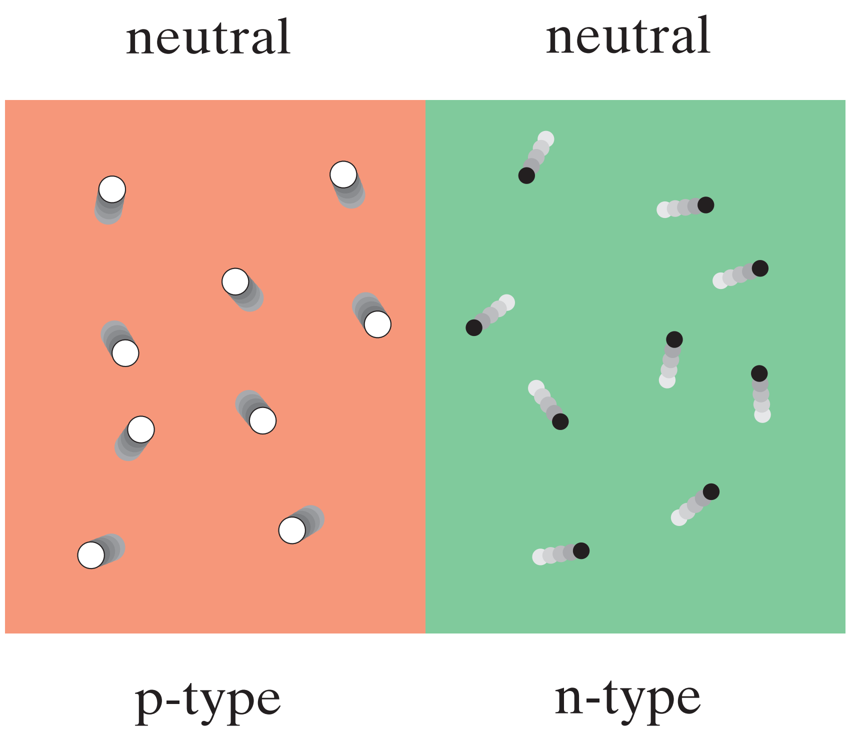
- new chemical structure and electronic properties
- nanocrystallinity: quantum confinement effects
- absorption happens in nanocrystalline layer

Outline



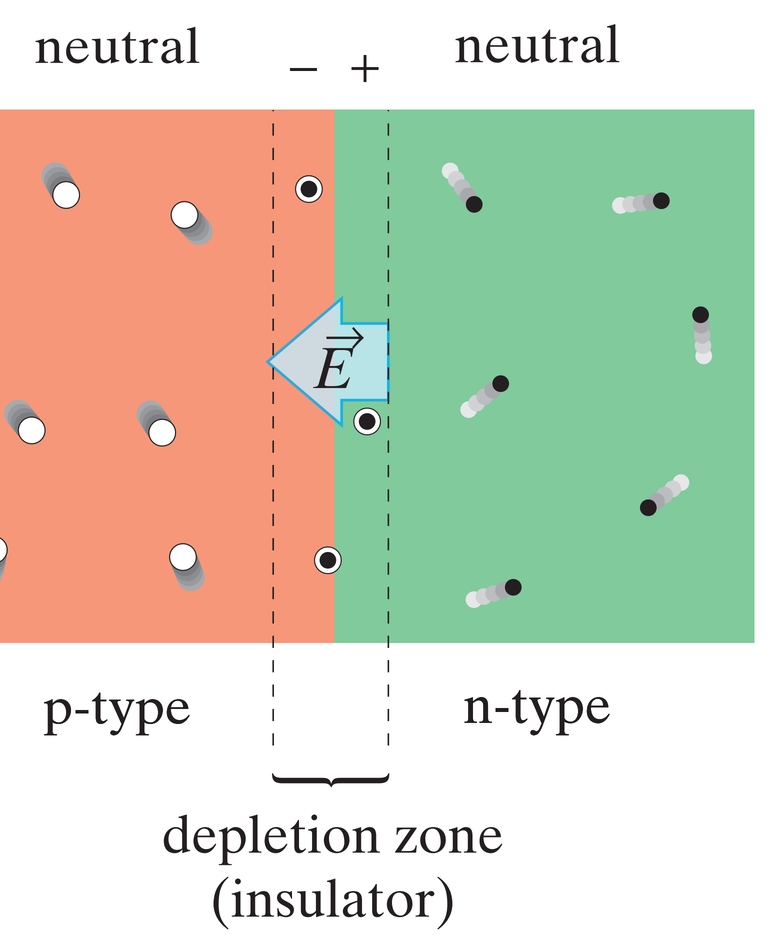
- high photon flux doping
- **photoelectron generation**
- photoconductive gain

Photoelectron generation



join acceptor and donor type Si…

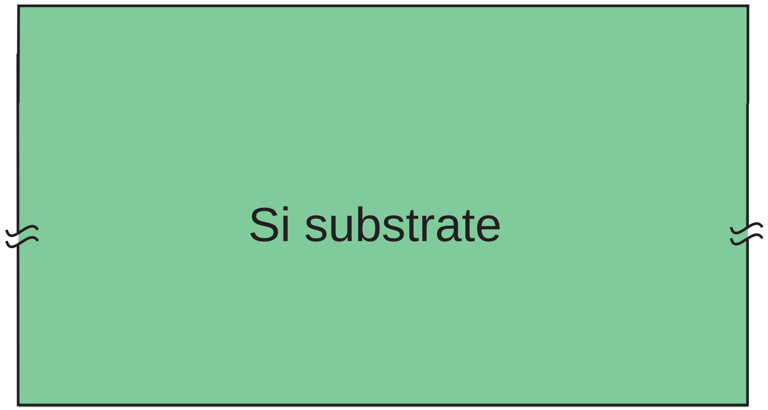
Photoelectron generation



non-conducting layer at junction

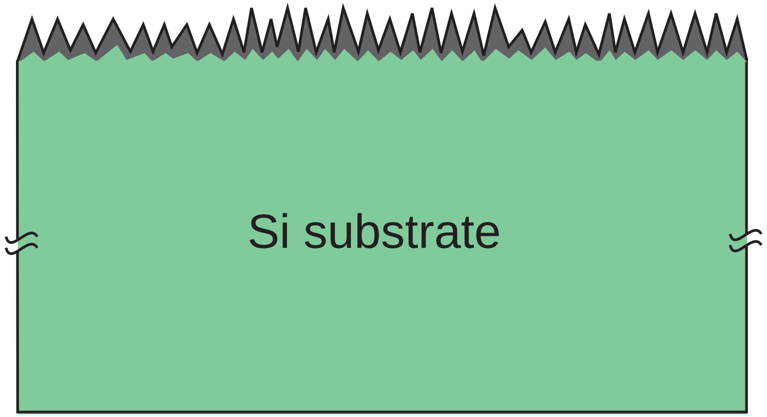
Photoelectron generation

black silicon/silicon junction



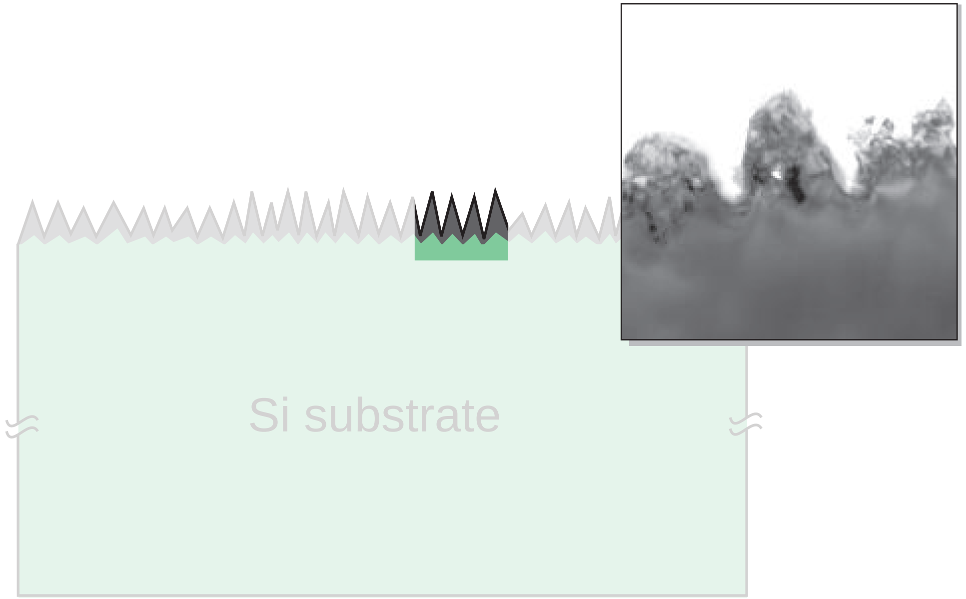
Photoelectron generation

black silicon/silicon junction



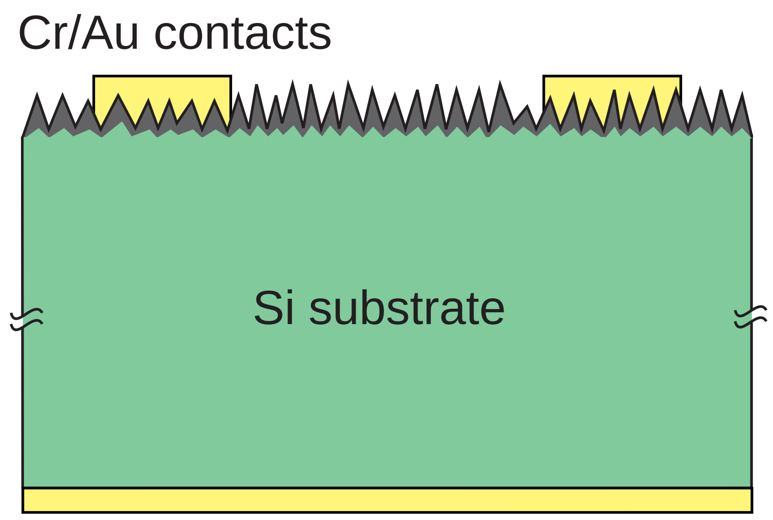
Photoelectron generation

black silicon/silicon junction



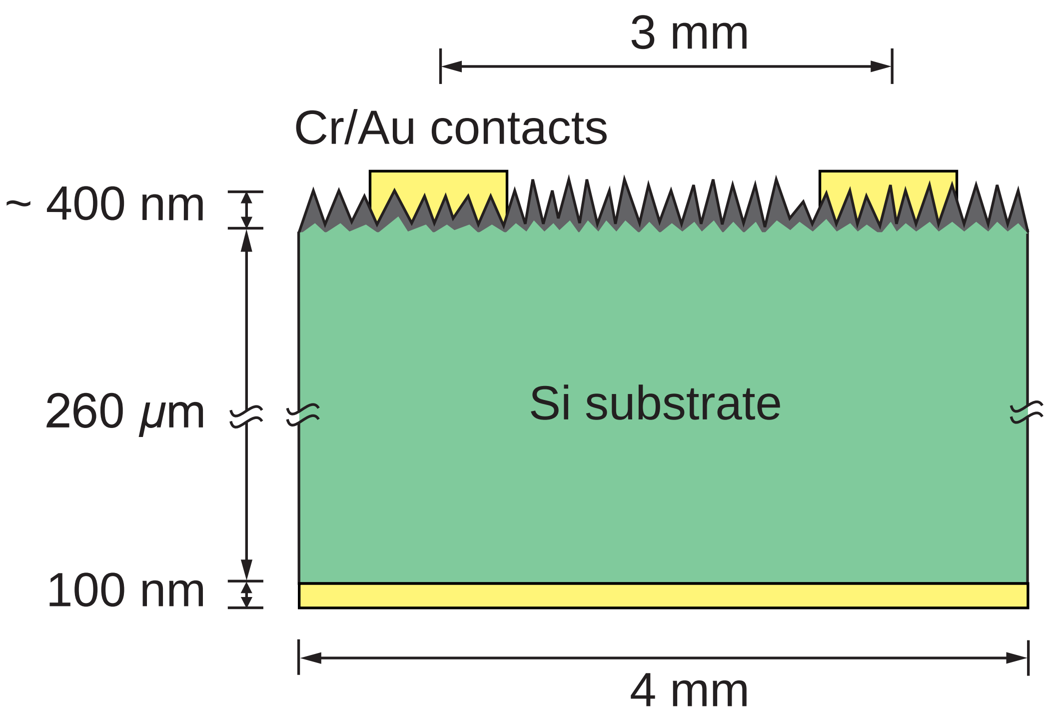
Photoelectron generation

black silicon/silicon junction



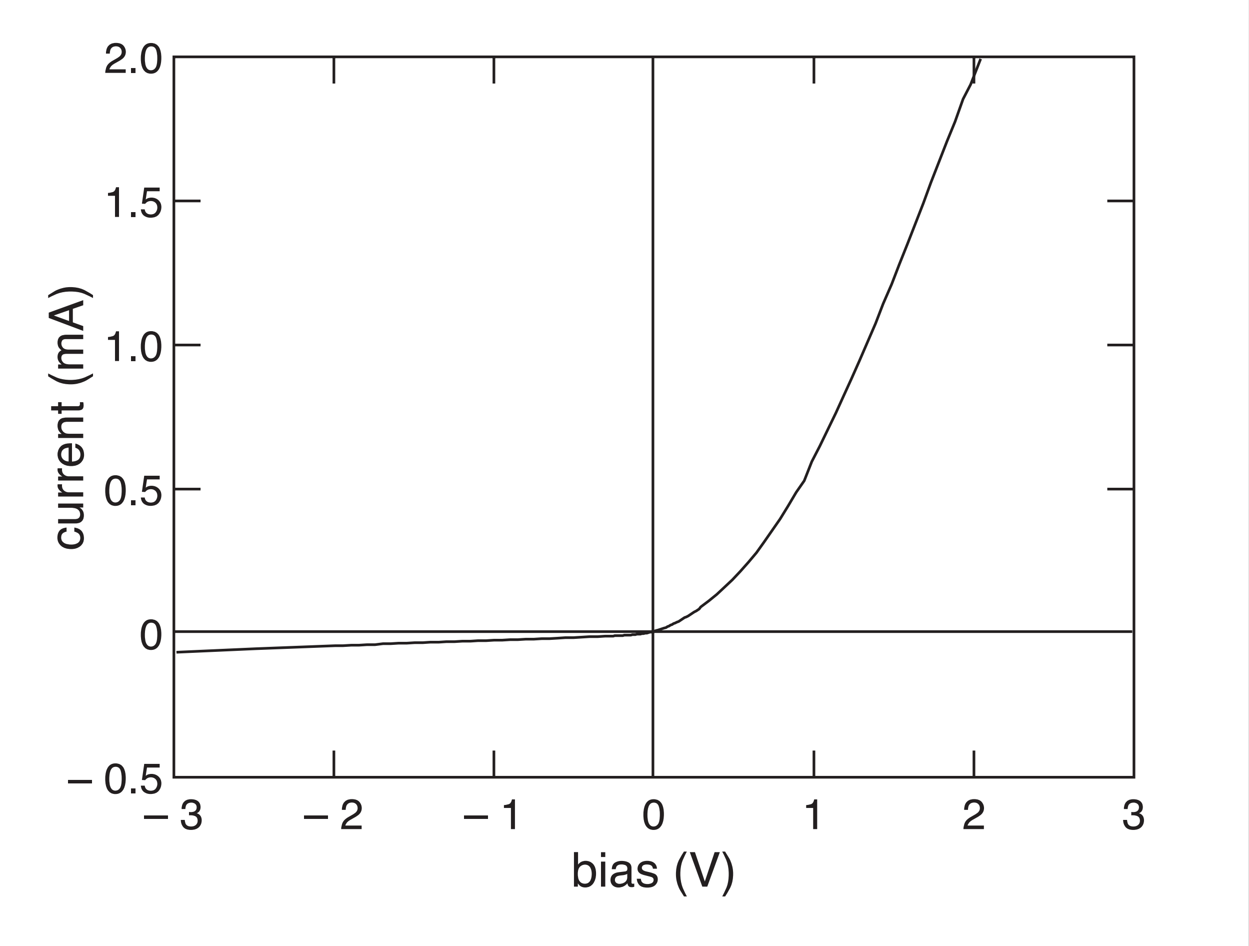
Photoelectron generation

black silicon/silicon junction

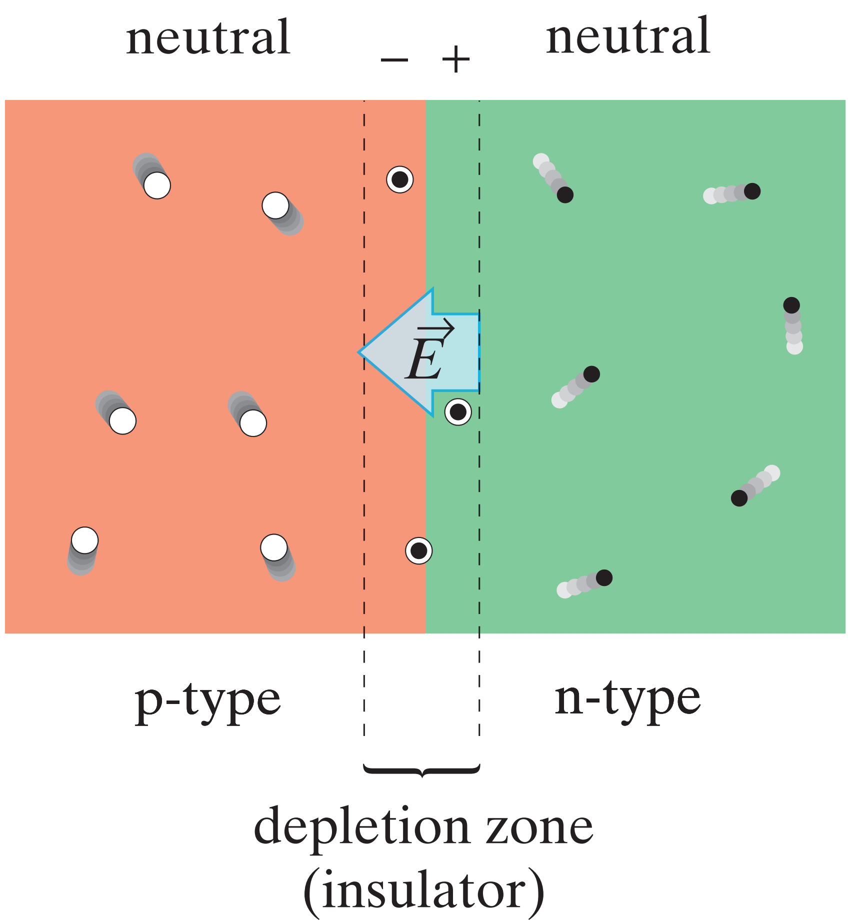


Photoelectron generation

IV characteristics

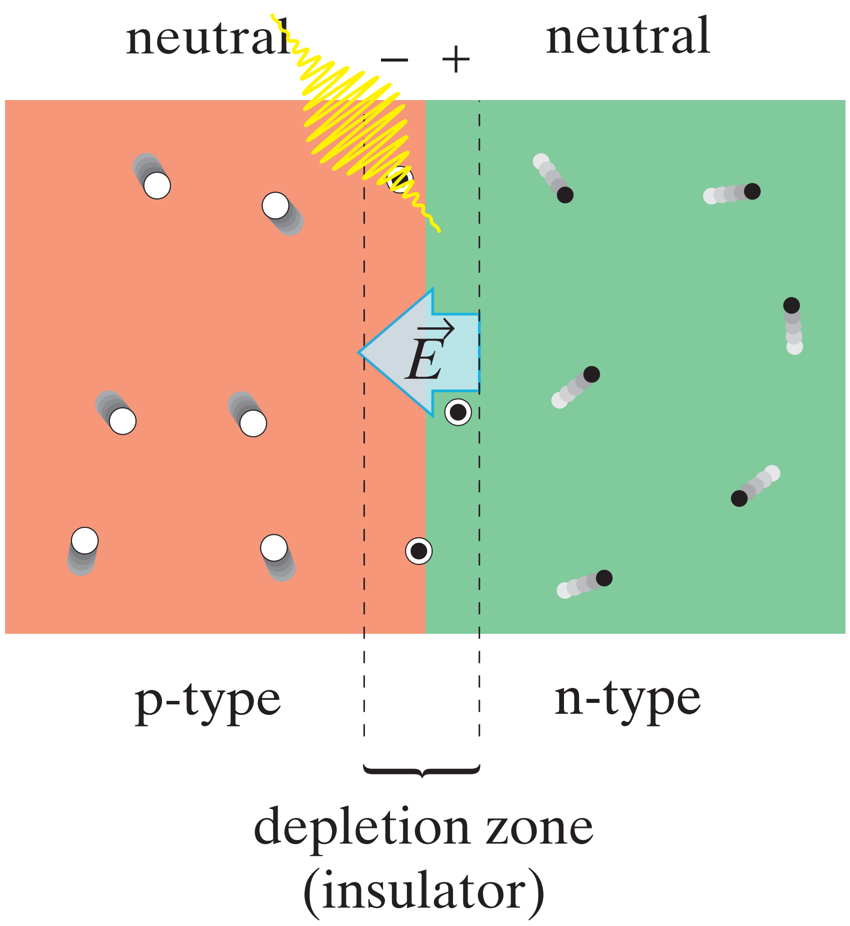


Photoelectron generation



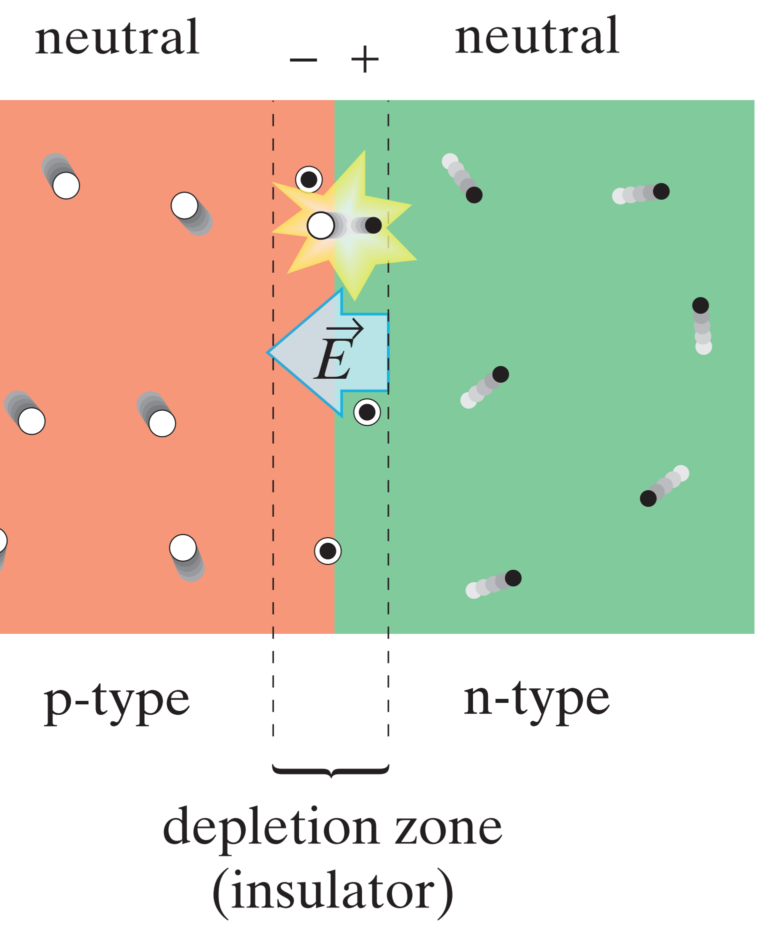
depletion layer can convert light into electric energy

Photoelectron generation



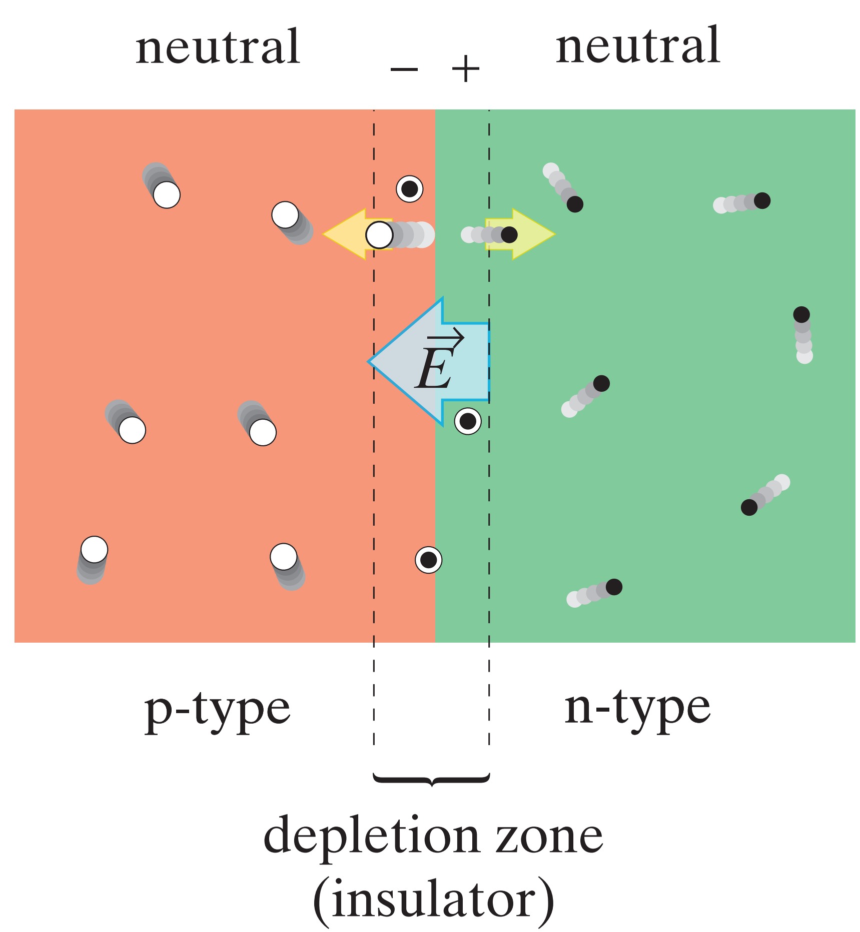
incident photon knocks out electron…

Photoelectron generation



…creating an electron-hole pair

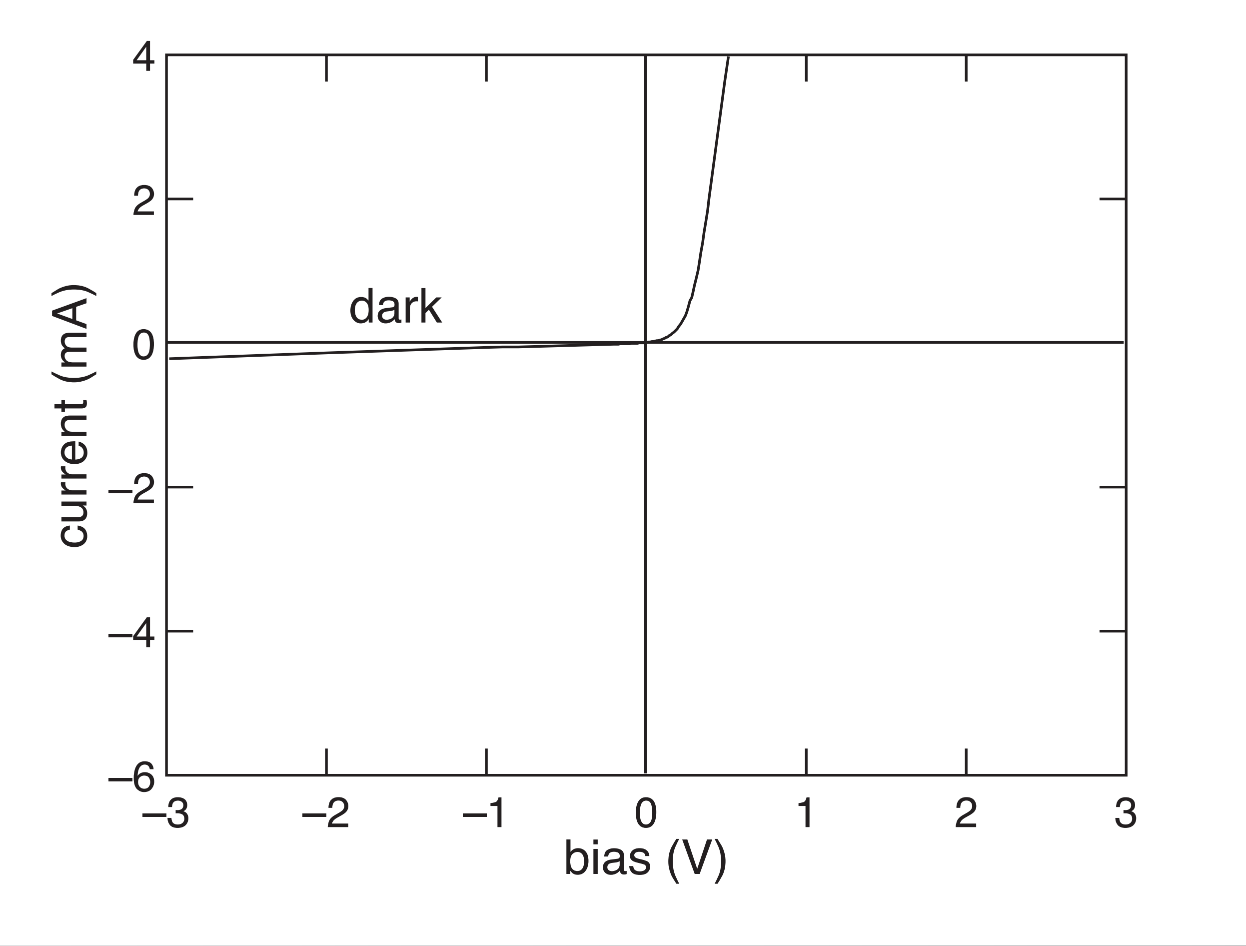
Photoelectron generation



E-field separates eh-pair, causing current

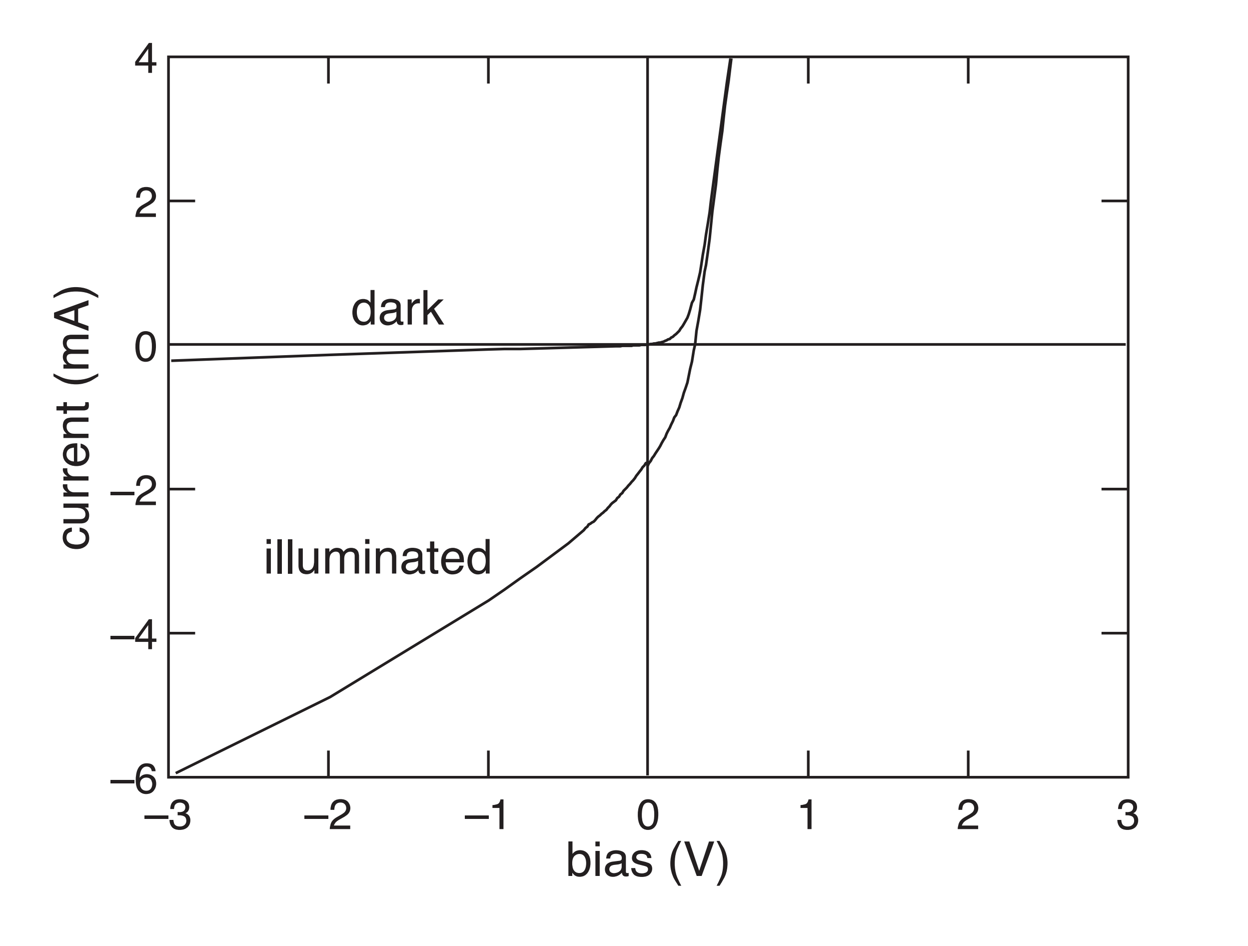
Photoelectron generation

IV characteristics



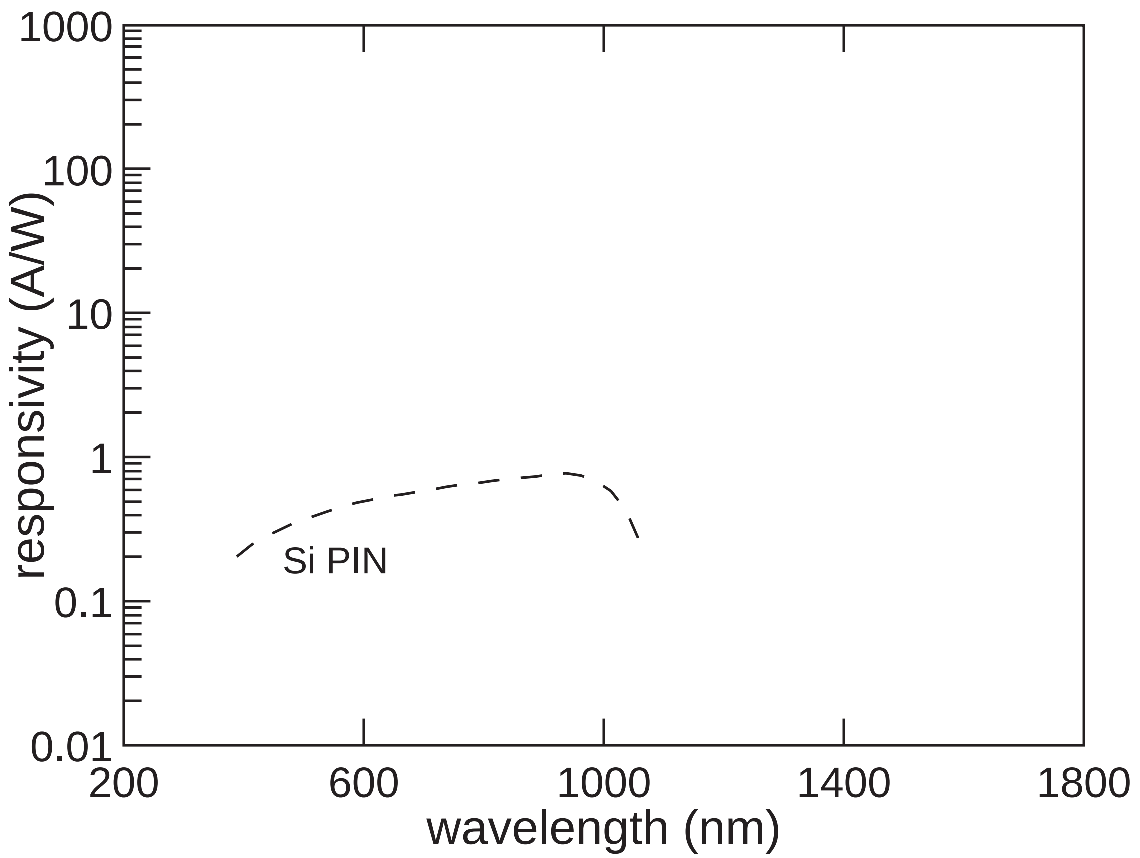
Photoelectron generation

IV characteristics



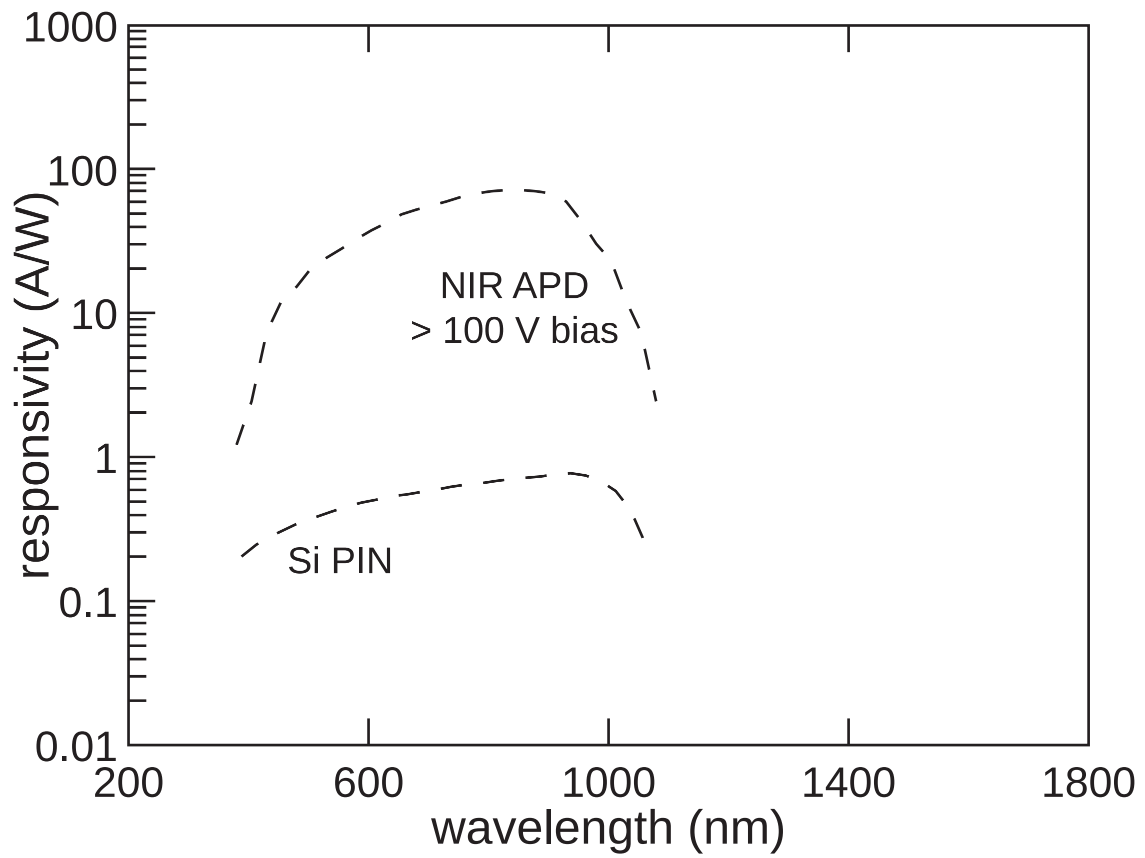
Photoelectron generation

responsivity



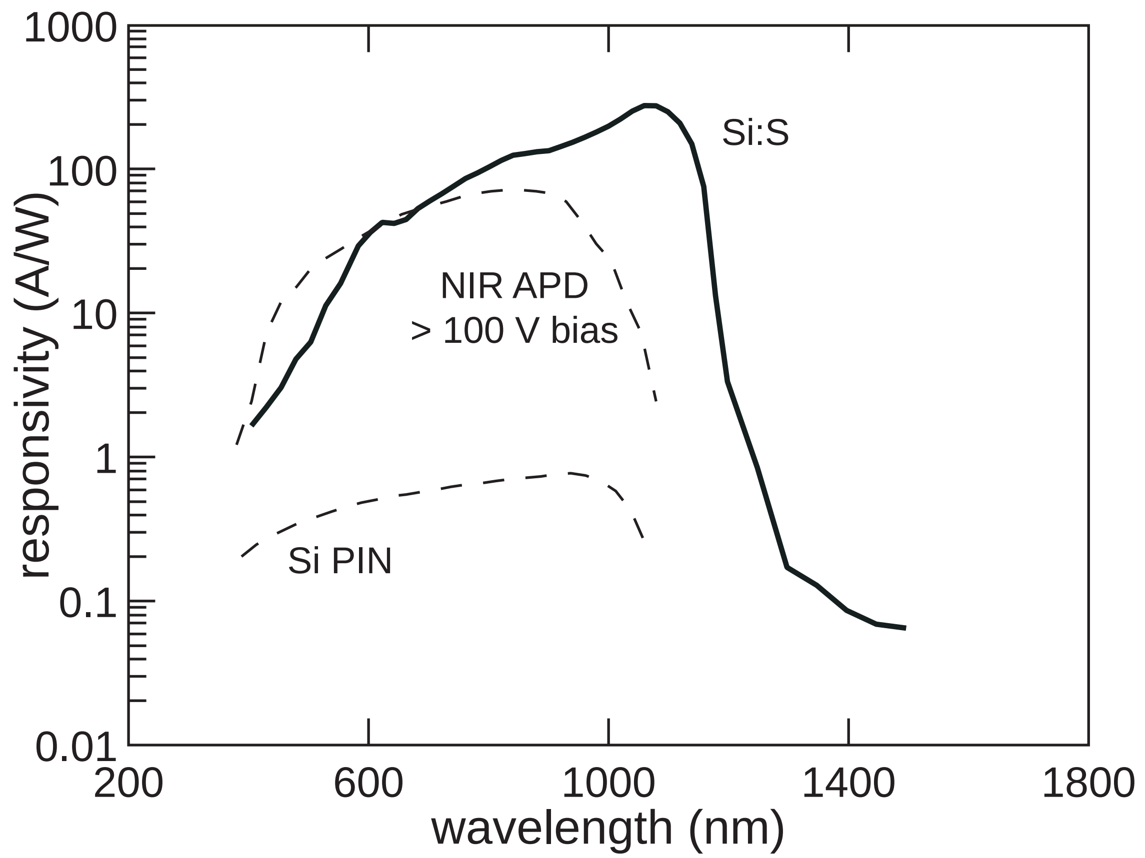
Photoelectron generation

responsivity



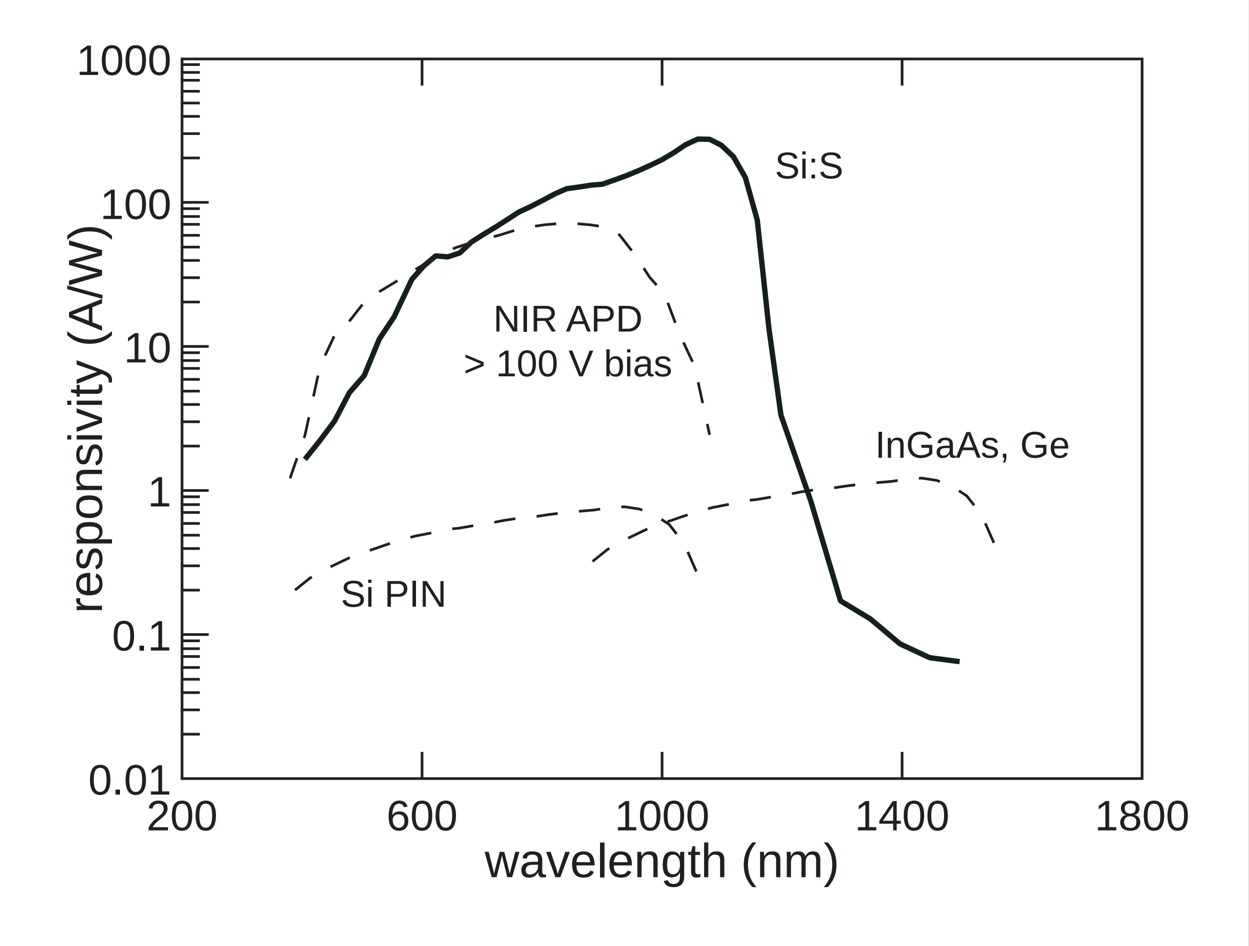
Photoelectron generation

responsivity



Photoelectron generation

responsivity



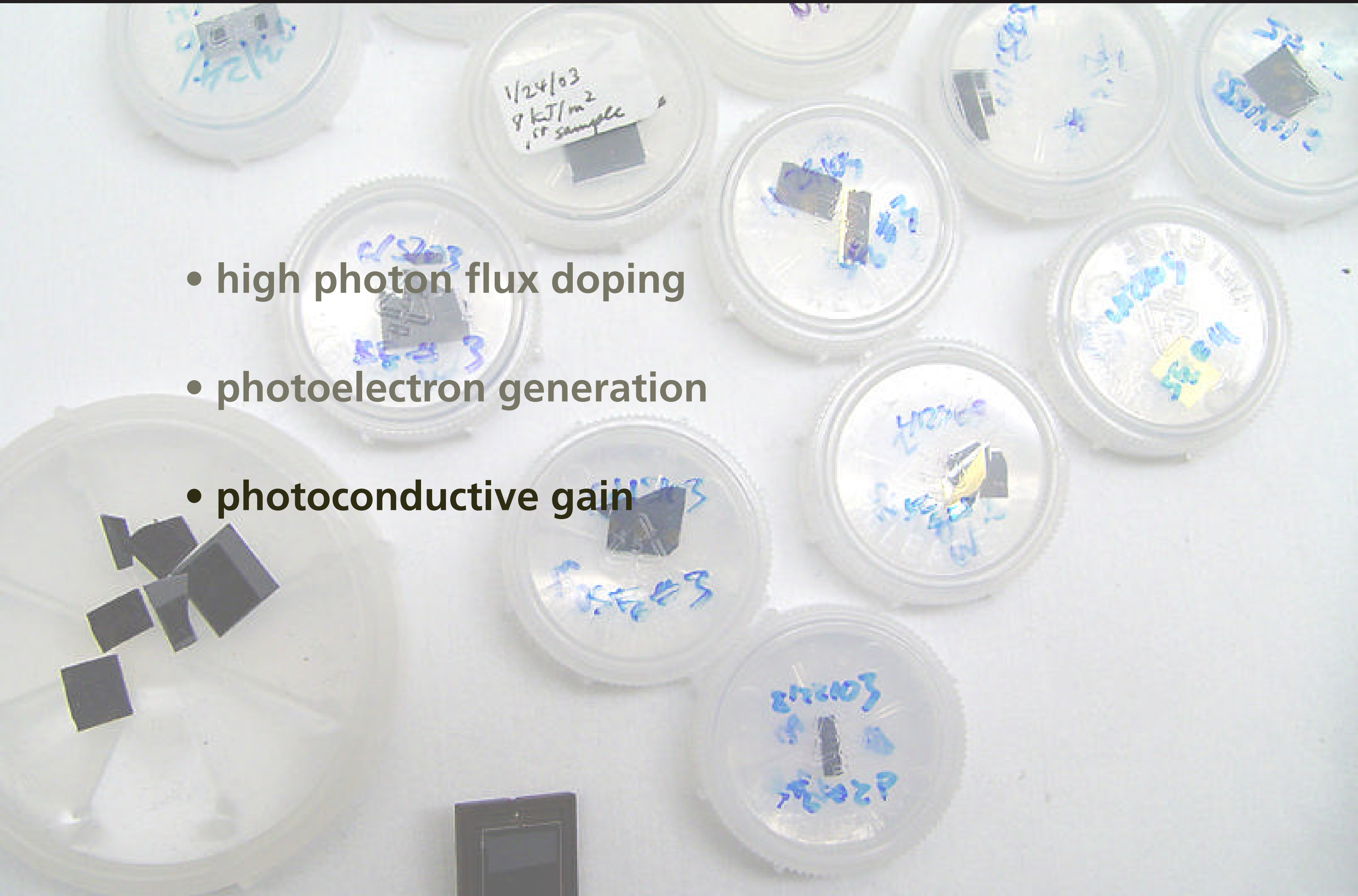
Photoelectron generation

Things to keep in mind

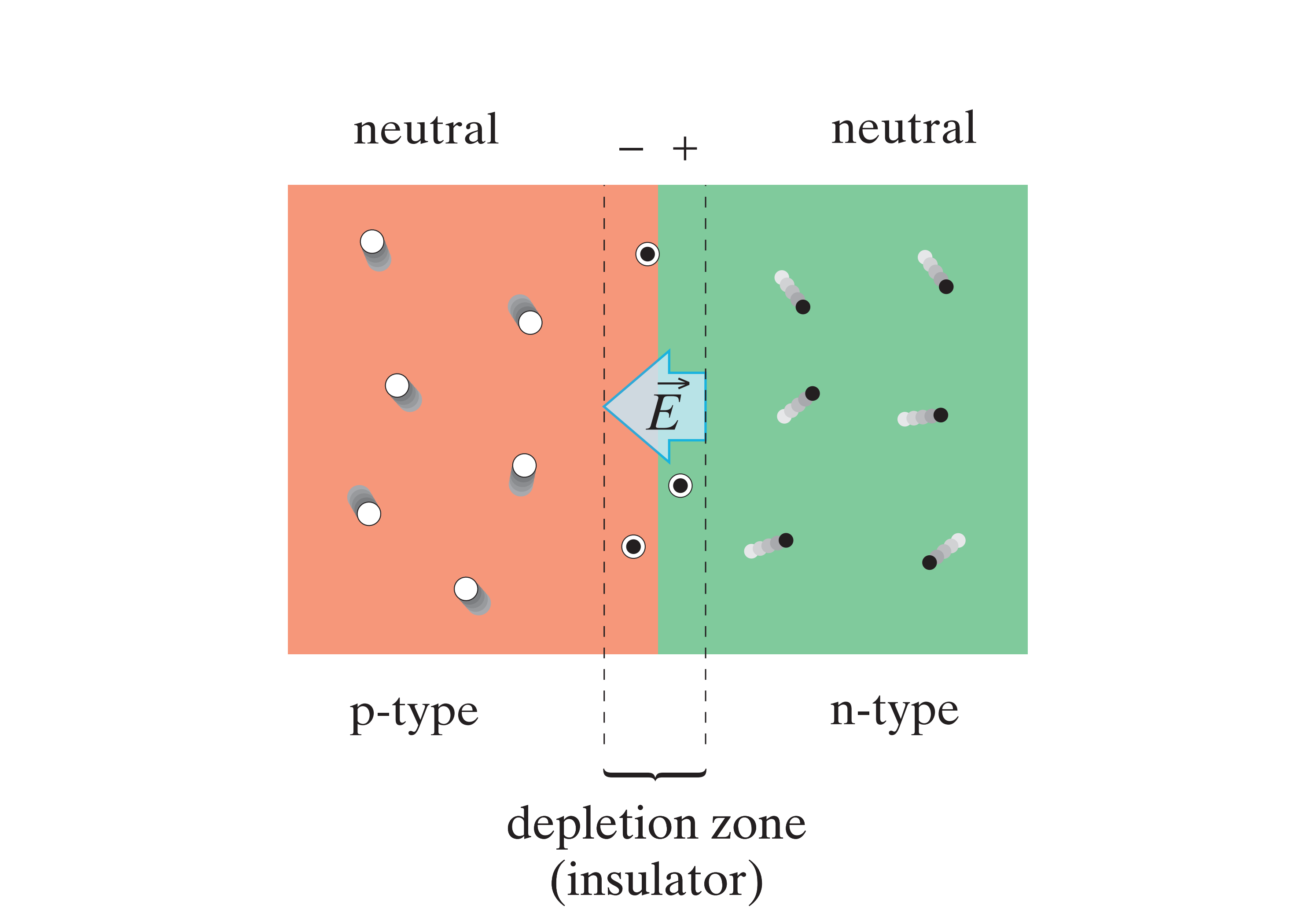
- can turn absorption into photoelectrons
- very high responsivity in VIS and IR
- quantum efficiency larger than one

Outline

- high photon flux doping
- photoelectron generation
- **photoconductive gain**

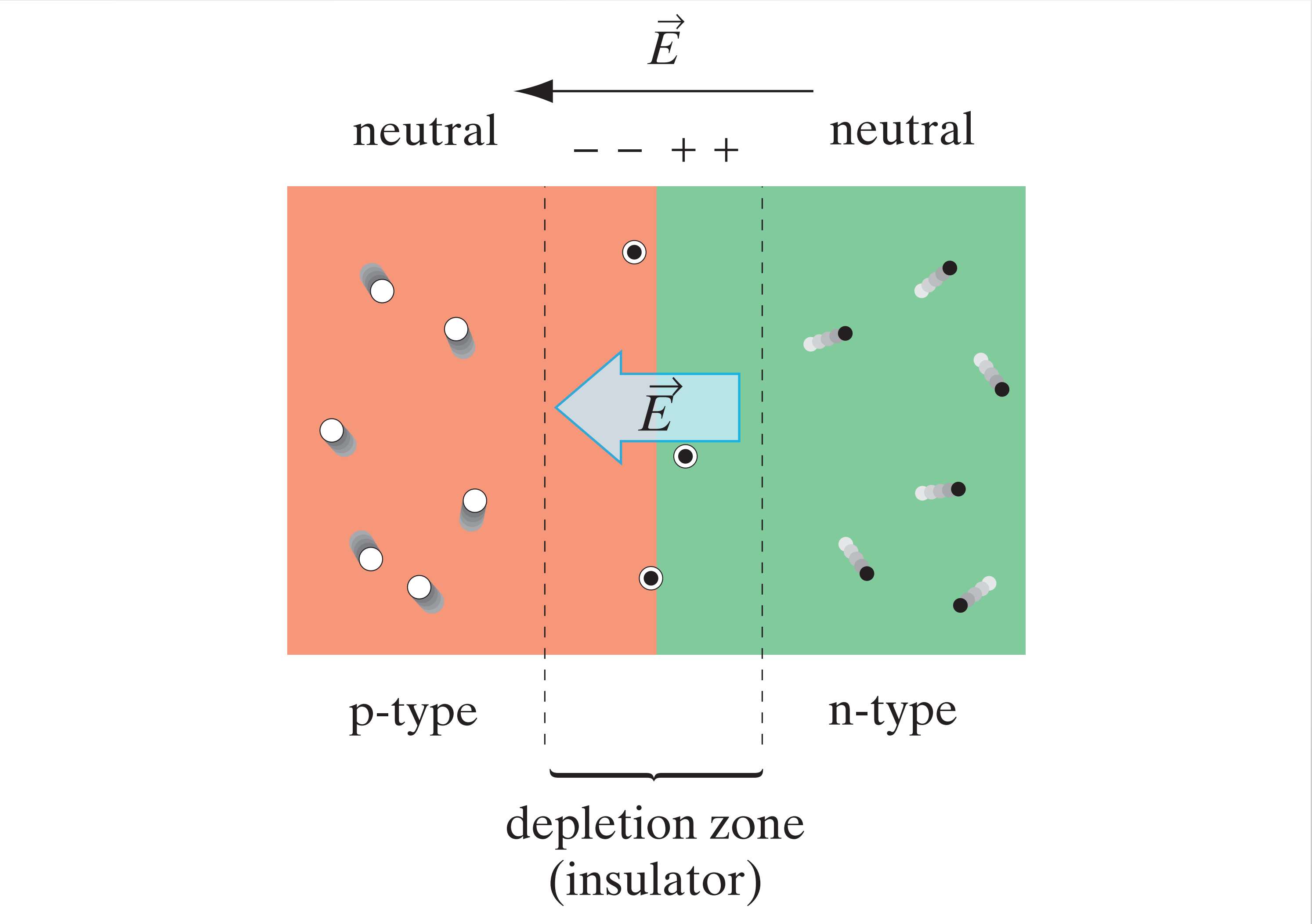


Photoconductive gain



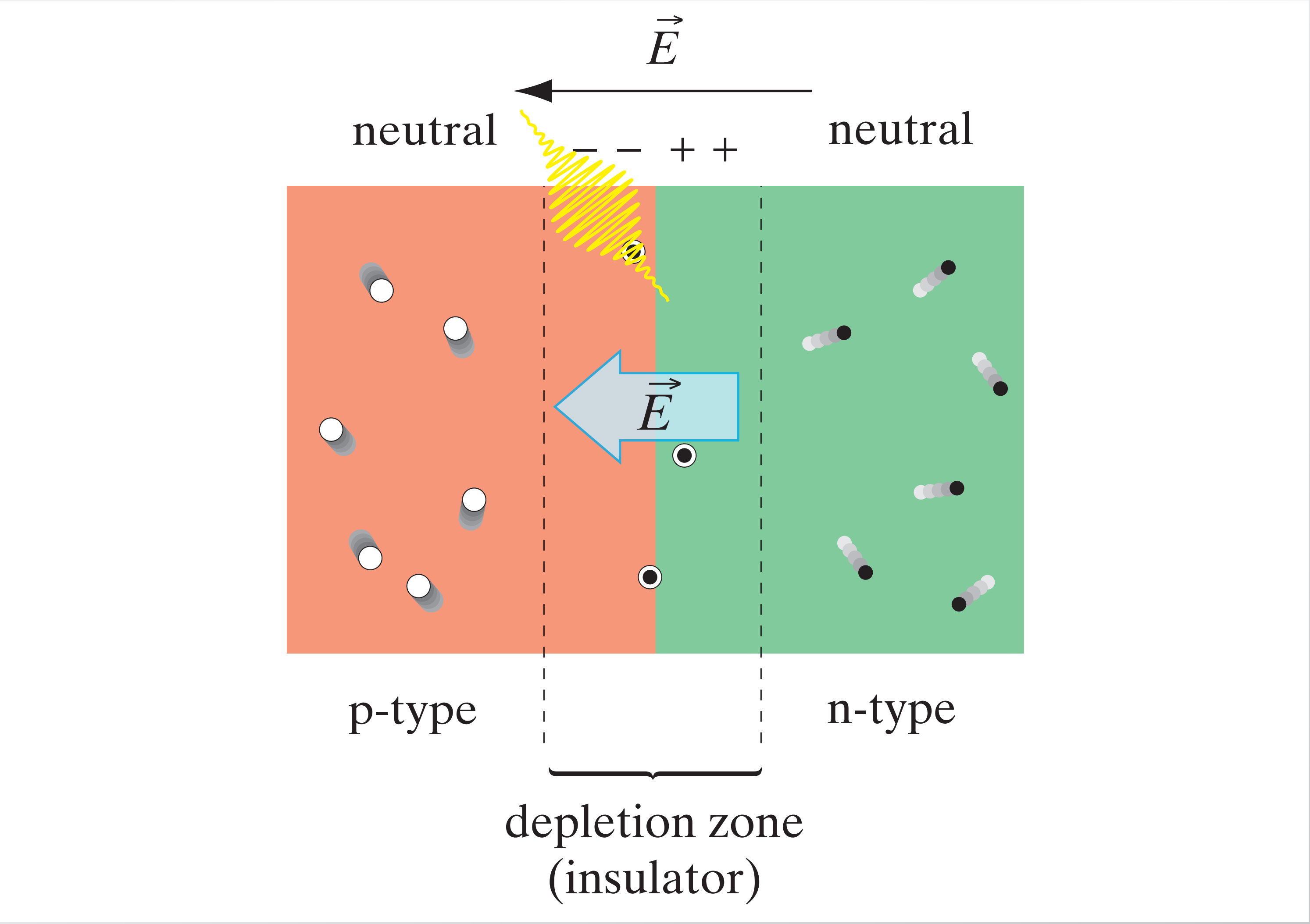
apply electric field…

Photoconductive gain



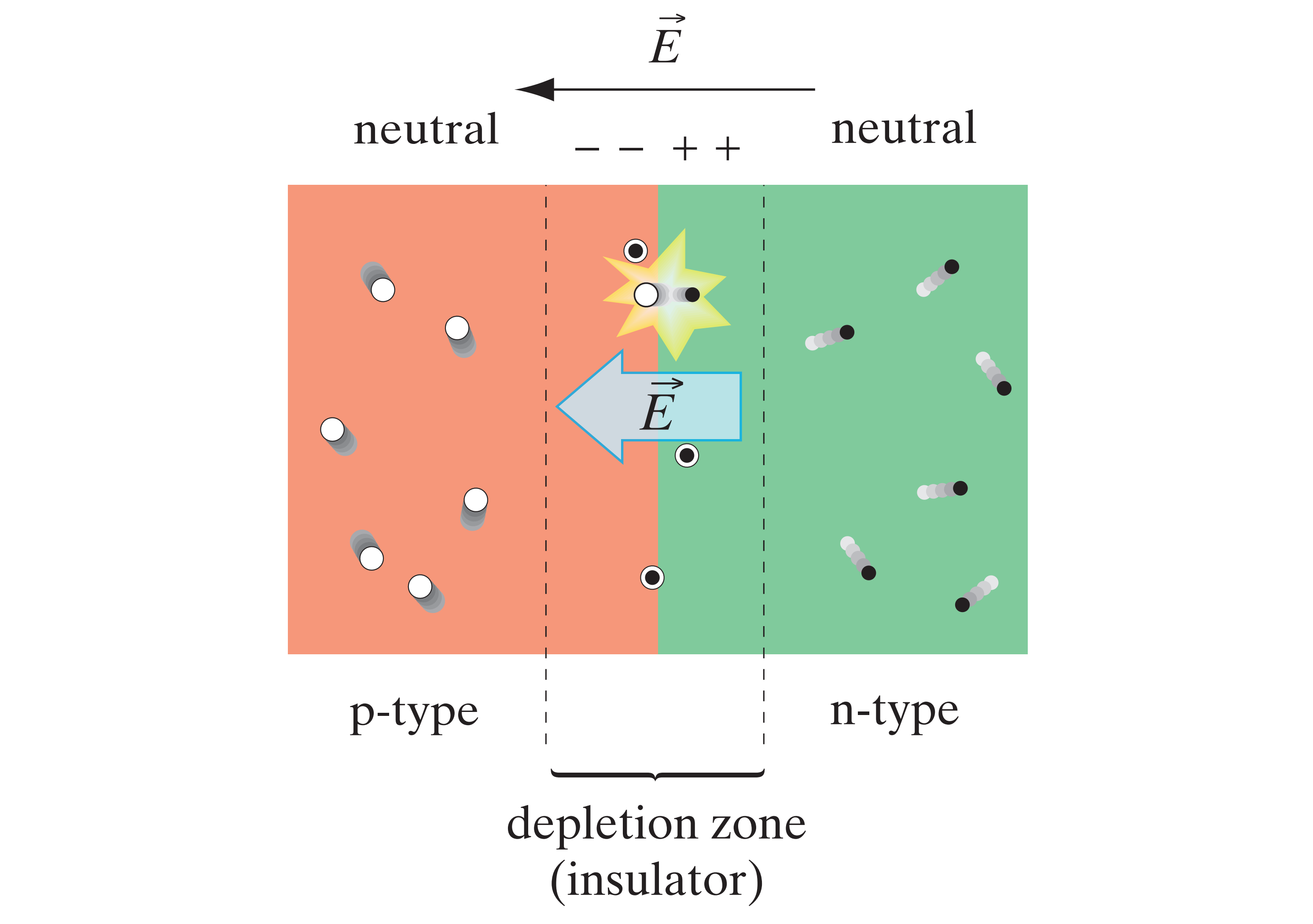
…and so depletion zone expands

Photoconductive gain



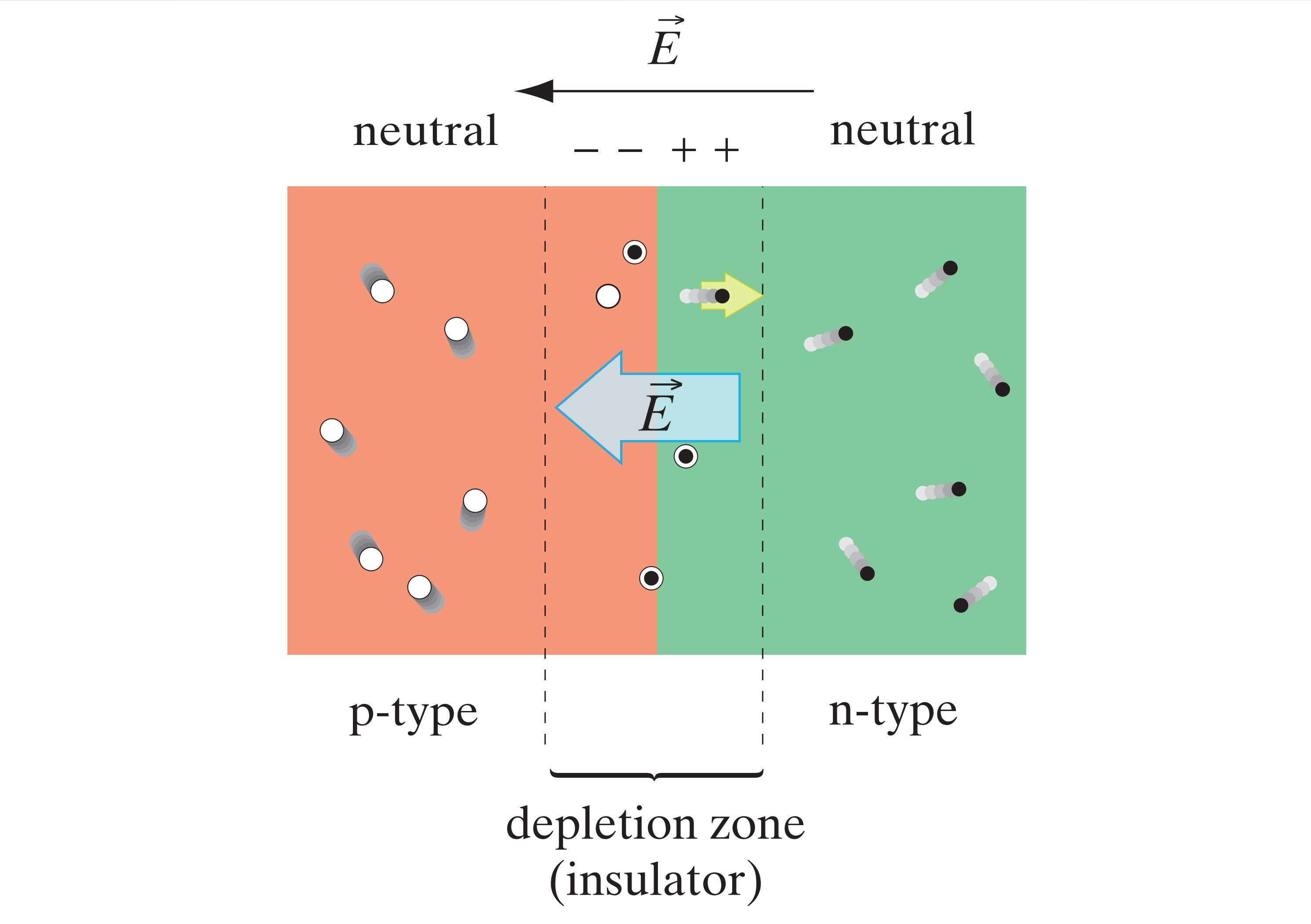
incident photon generates electron-hole pair

Photoconductive gain



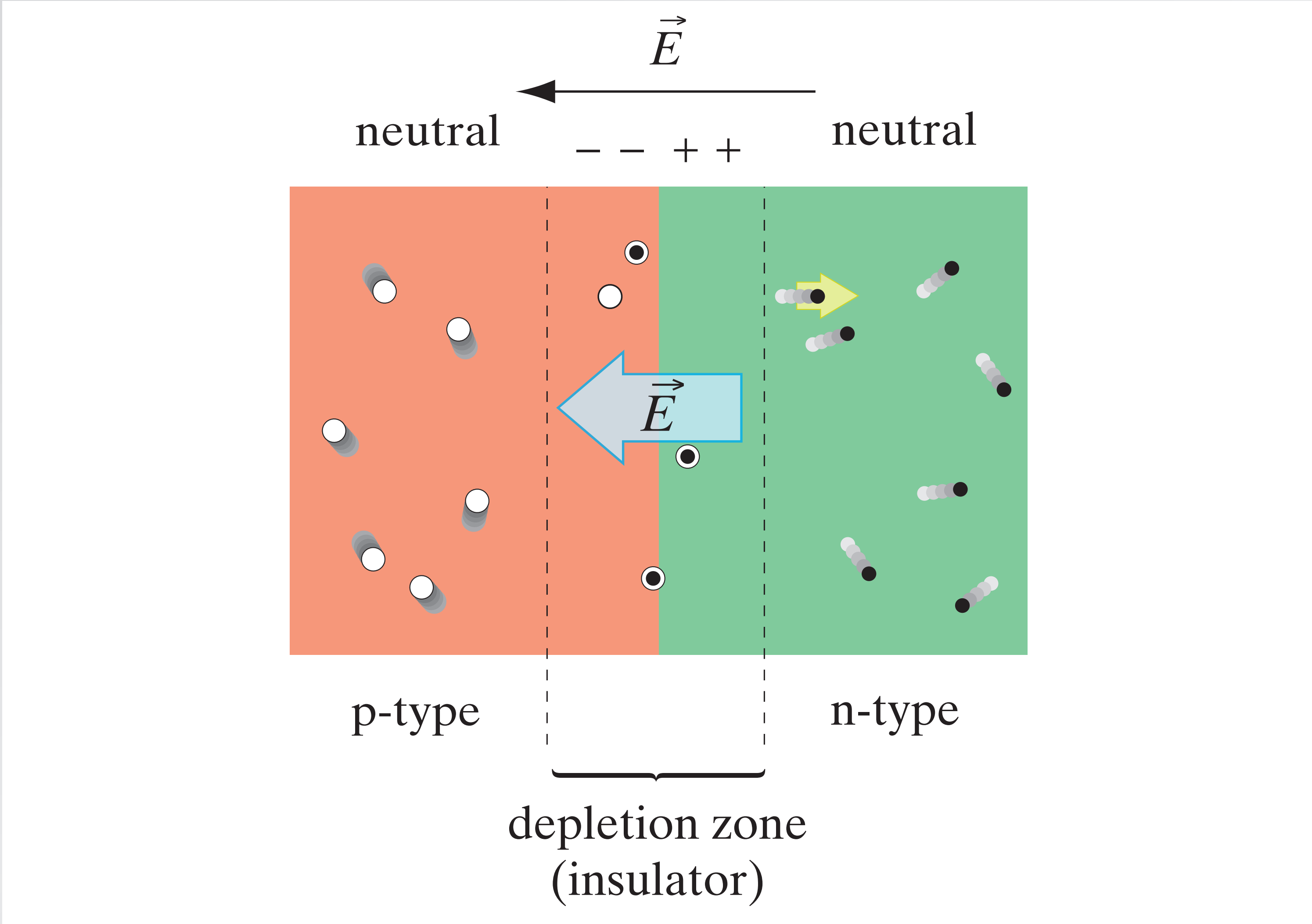
incident photon generates electron-hole pair

Photoconductive gain



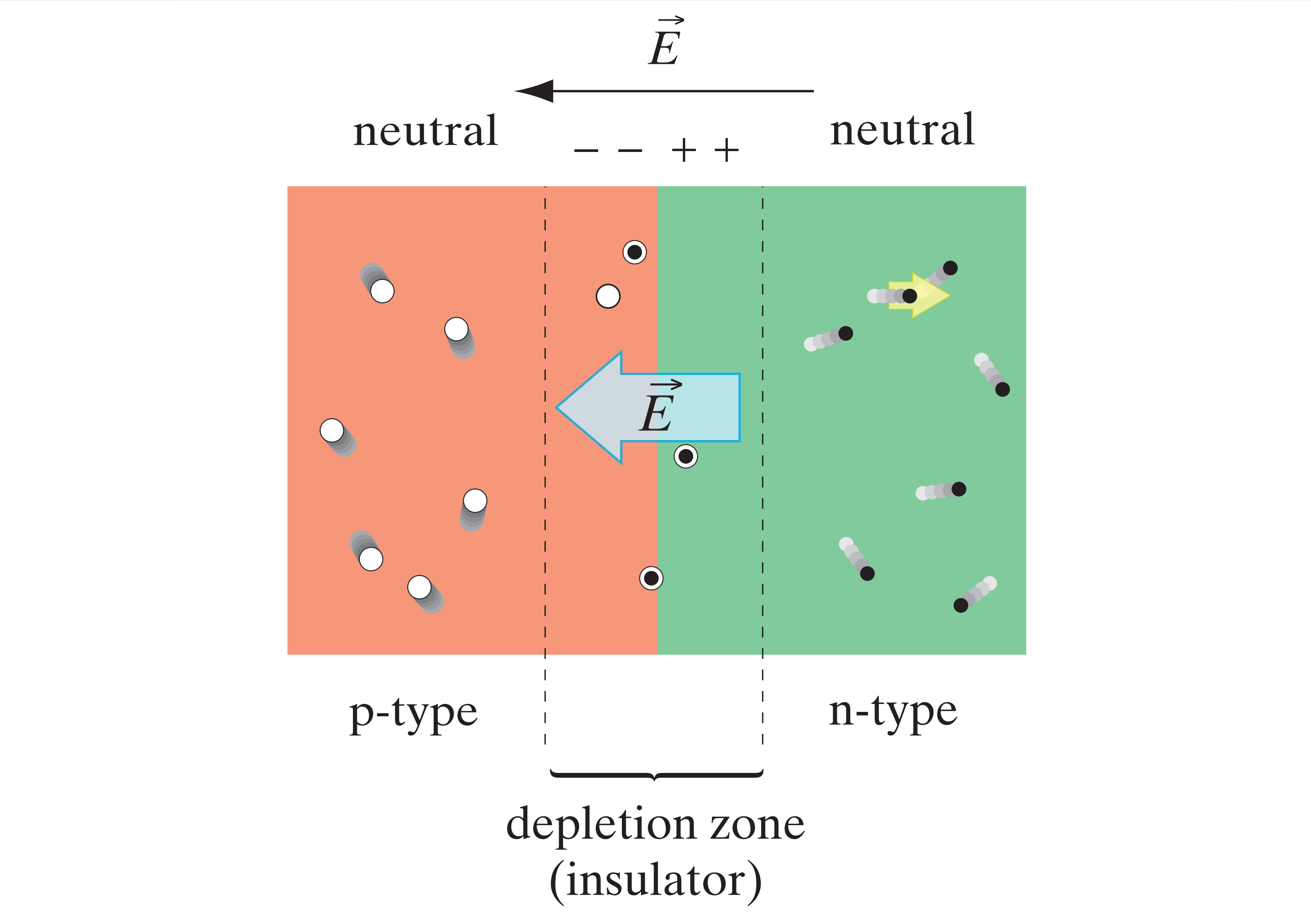
hole is trapped, electron accelerates…

Photoconductive gain



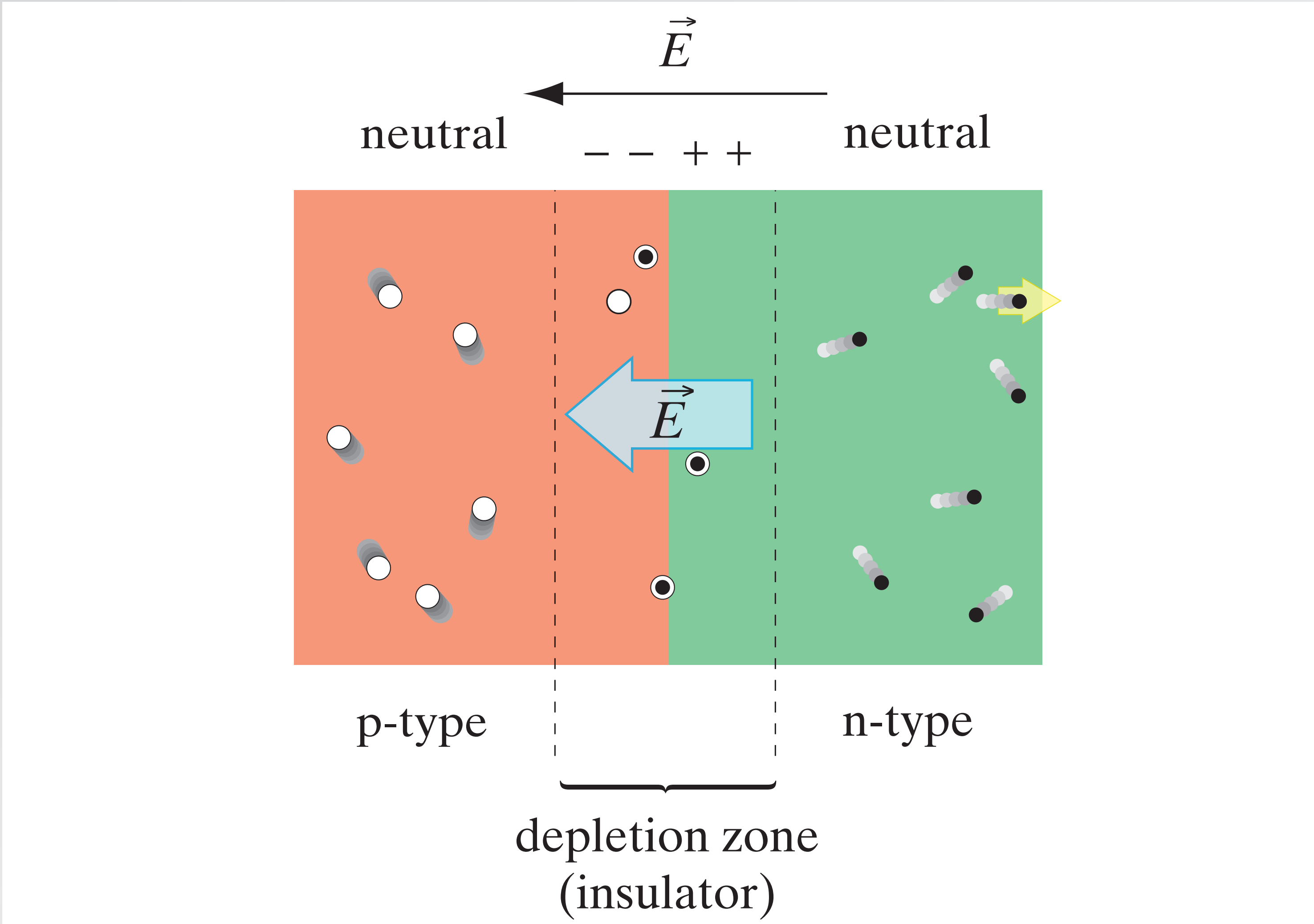
hole is trapped, electron accelerates…

Photoconductive gain



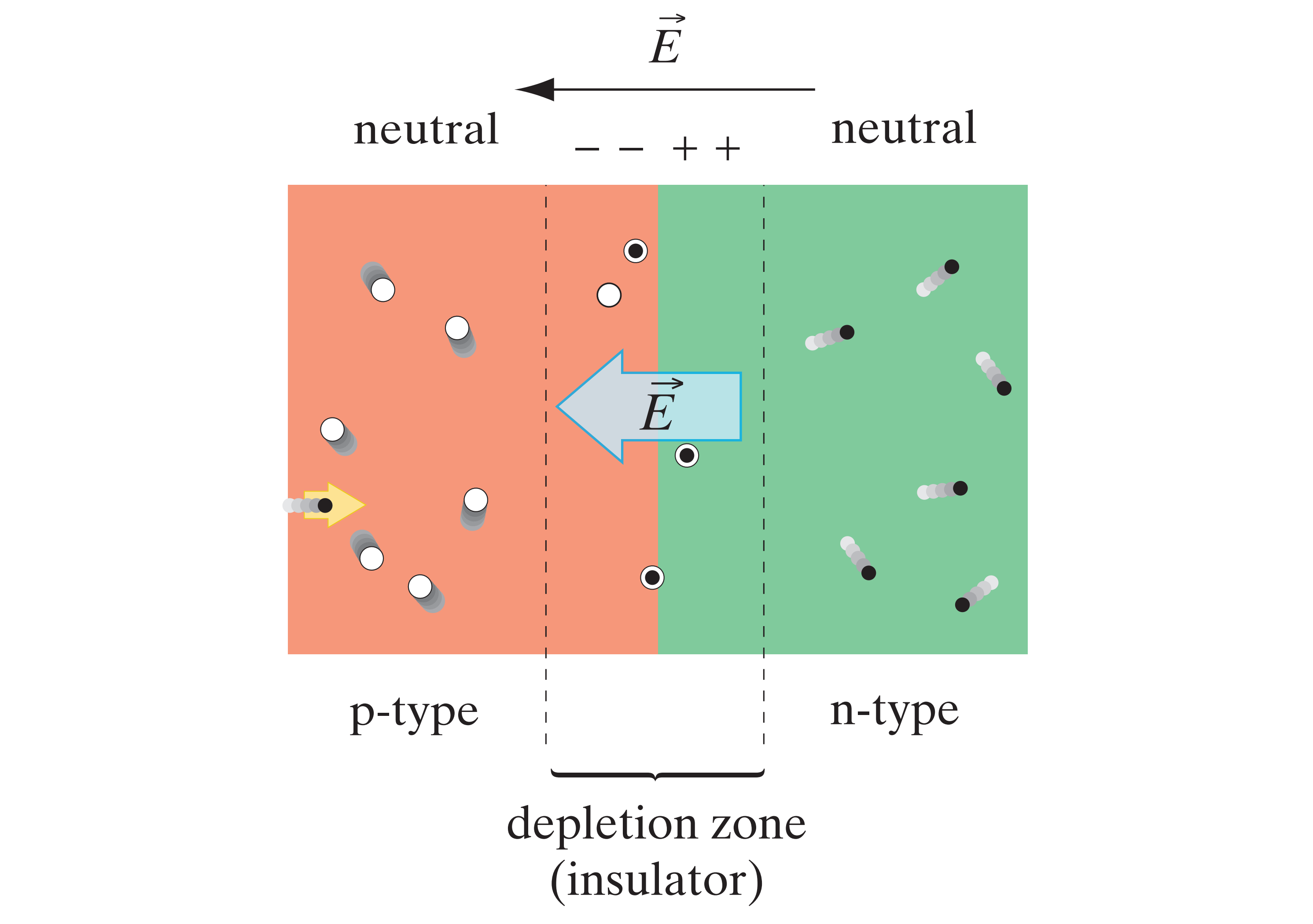
hole is trapped, electron accelerates…

Photoconductive gain



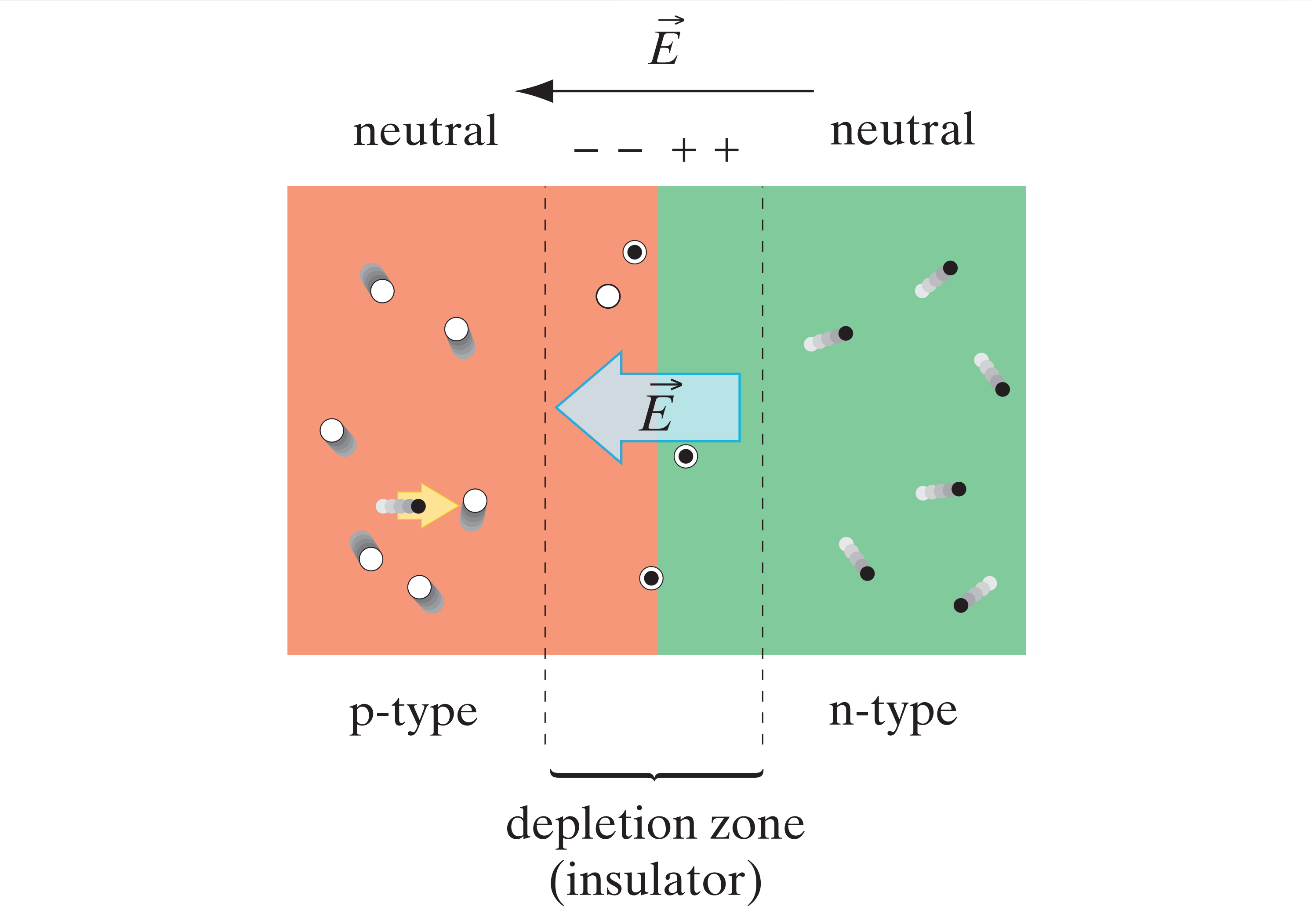
…exits sample…

Photoconductive gain



…and source supplies a new electron

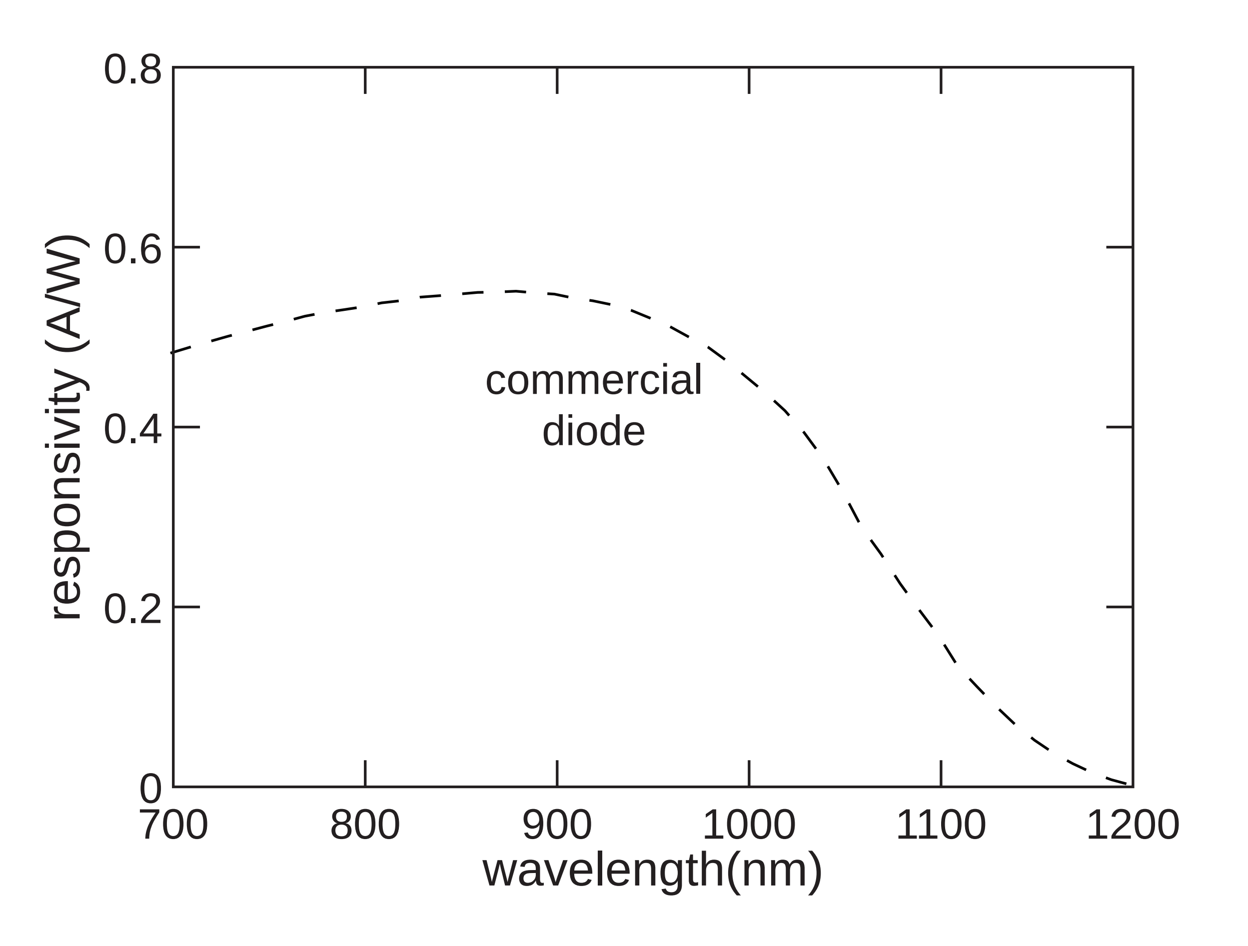
Photoconductive gain



…and source supplies a new electron

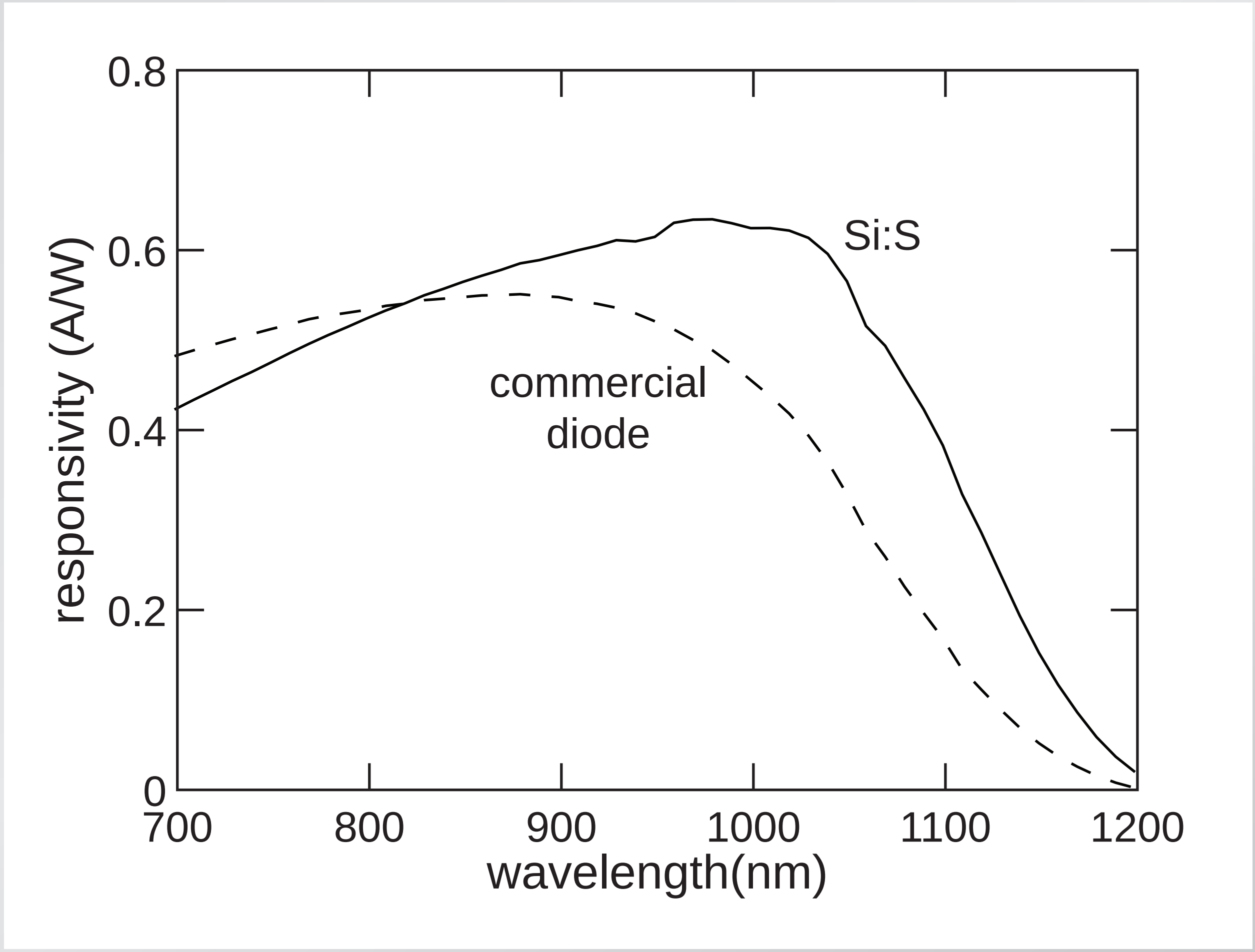
Photoconductive gain

responsivity at zero bias



Photoconductive gain

doubled quantum efficiency around 1.1 μm

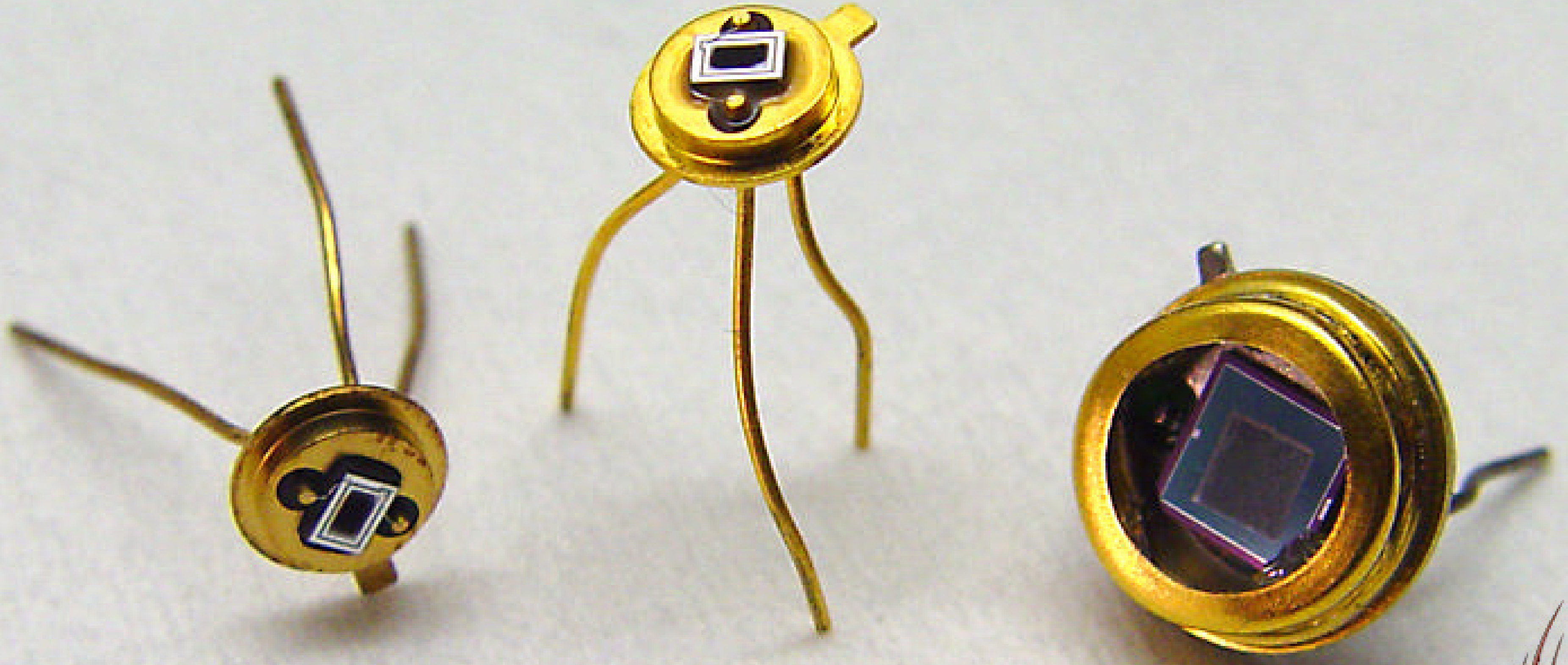


Photoconductive gain

Things to keep in mind

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

Photoconductive gain

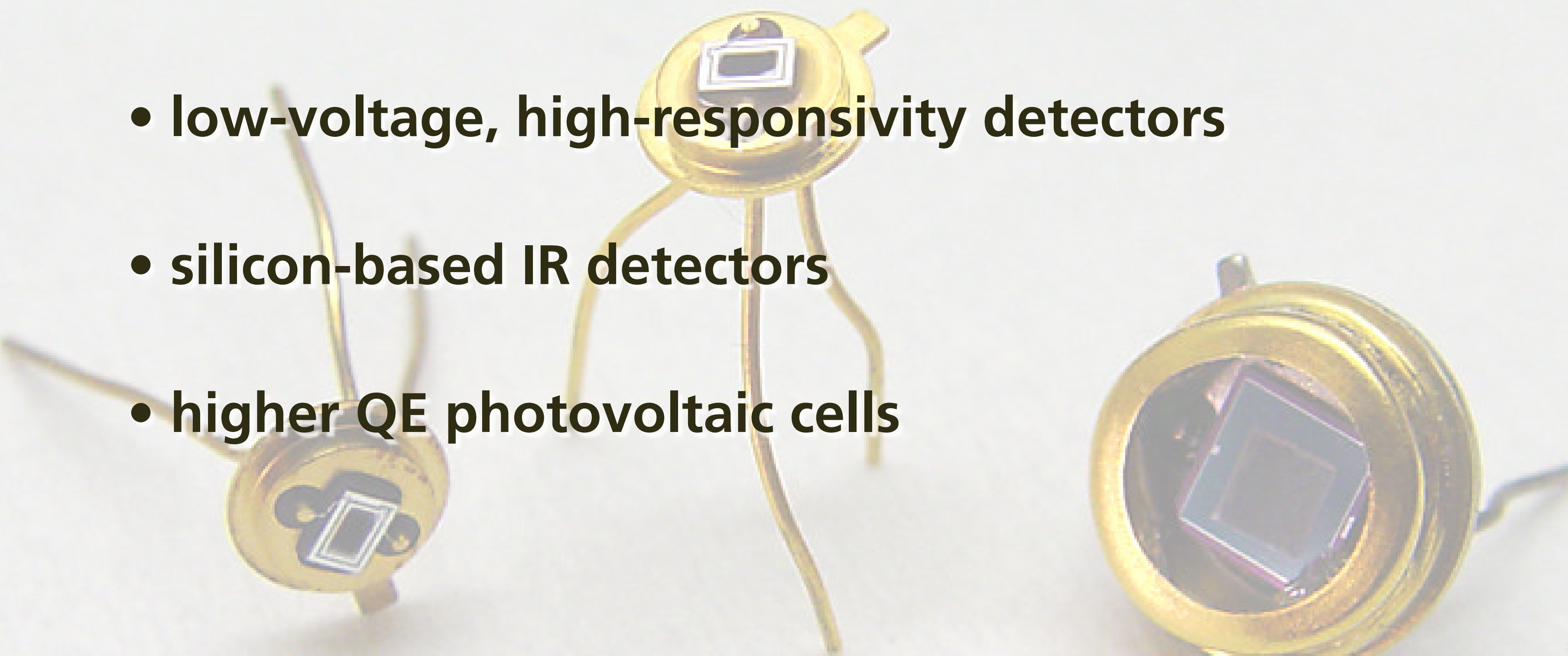


http://www.sionyxinc.com

SiOnyx

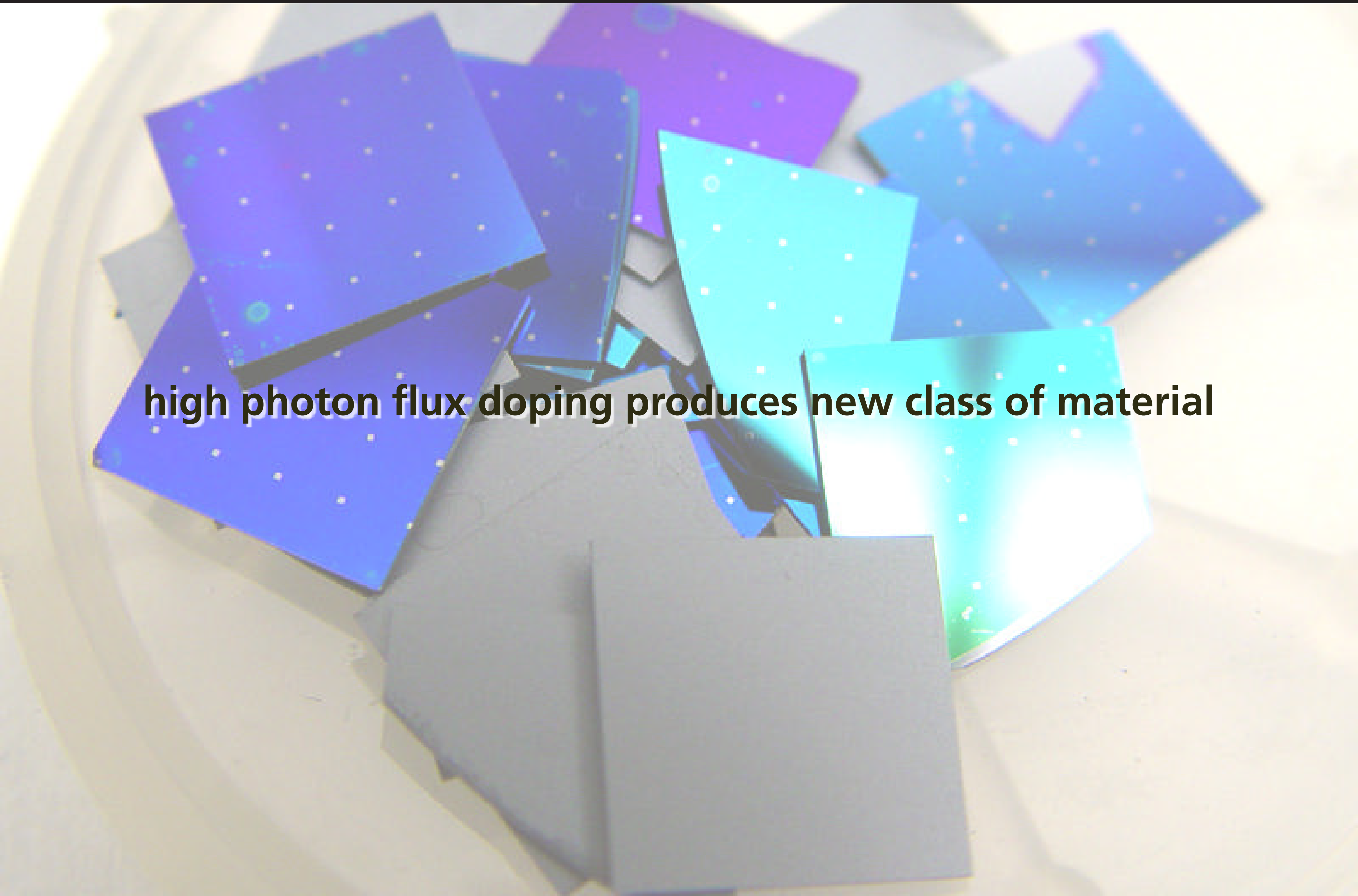
Photoconductive gain

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



http://www.sionyxinc.com

Summary



high photon flux doping produces new class of material

Funding:

Army Research Office
DARPA
Department of Energy
NDSEG

for a copy of this presentation:

http://mazur-www.harvard.edu