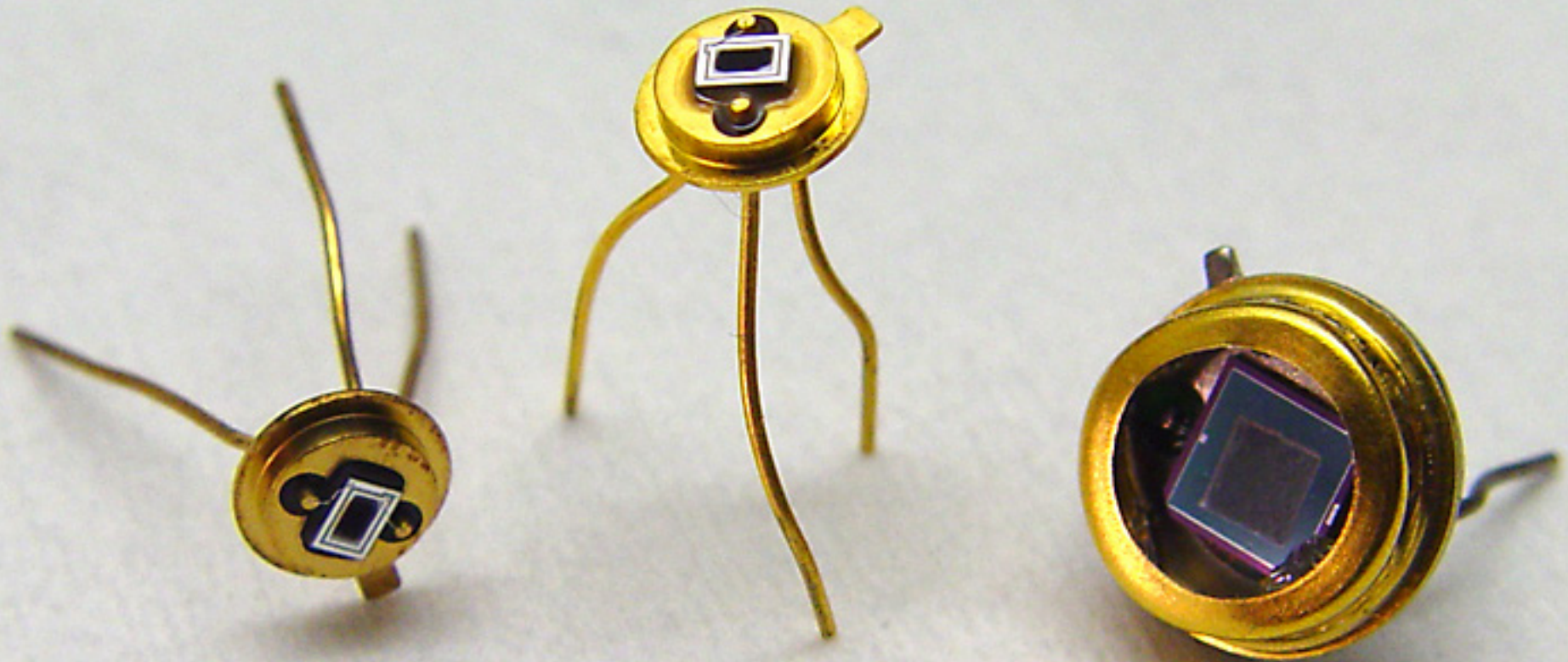


Pushing a physics discovery towards commercial impact

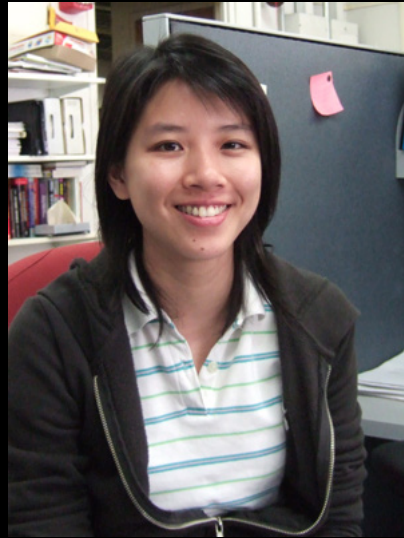


REU Seminar
Harvard University
Cambridge, MA, 16 July 2014





Renee Sher



Yu-Ting Lin



Kasey Philips

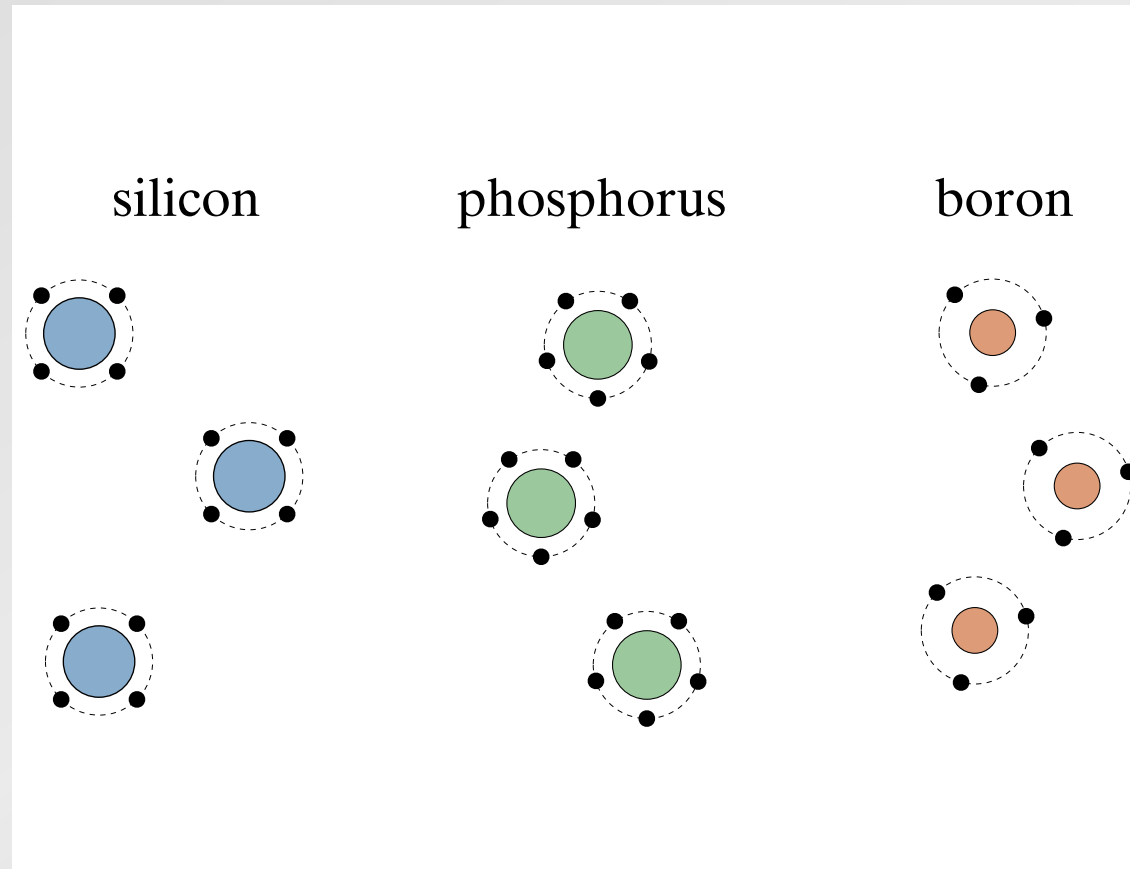


Ben Franta



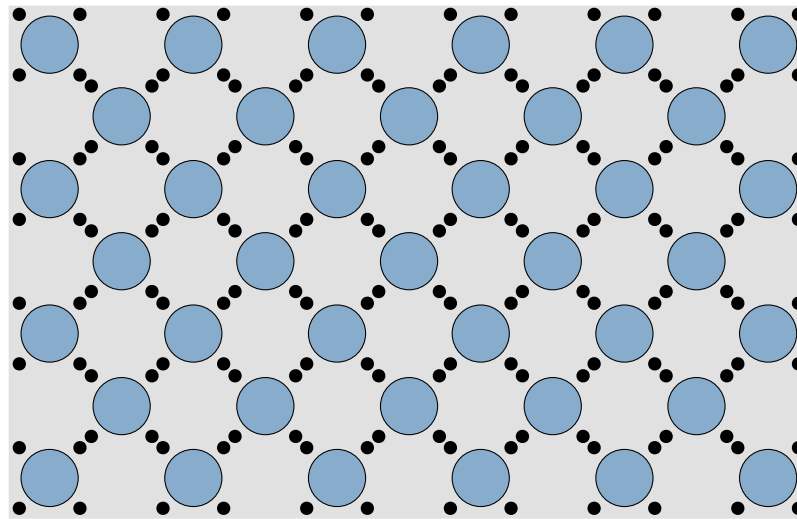
eric_mazur

Introduction



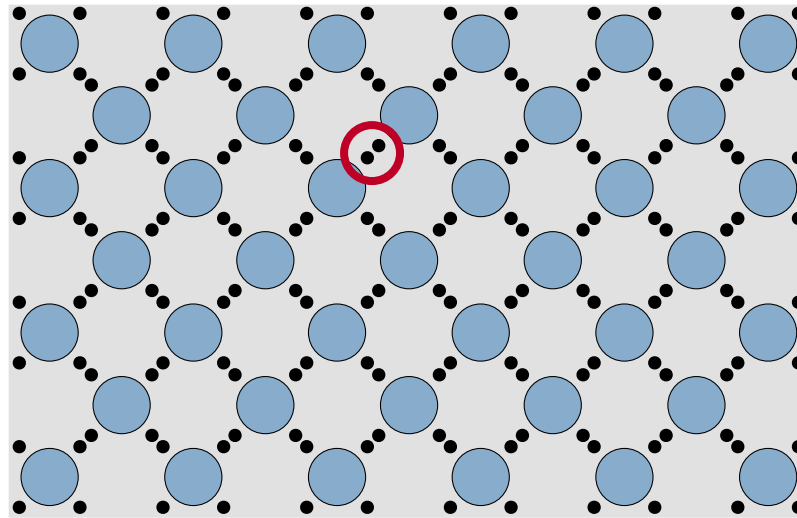
outer ("valence") electrons determine electronic properties

Introduction



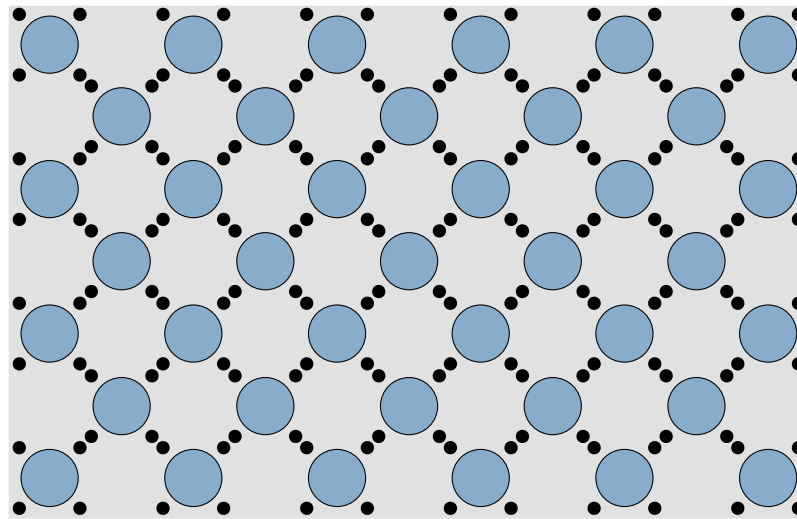
pure ("intrinsic") silicon

Introduction



electrons in covalent bond are immobile

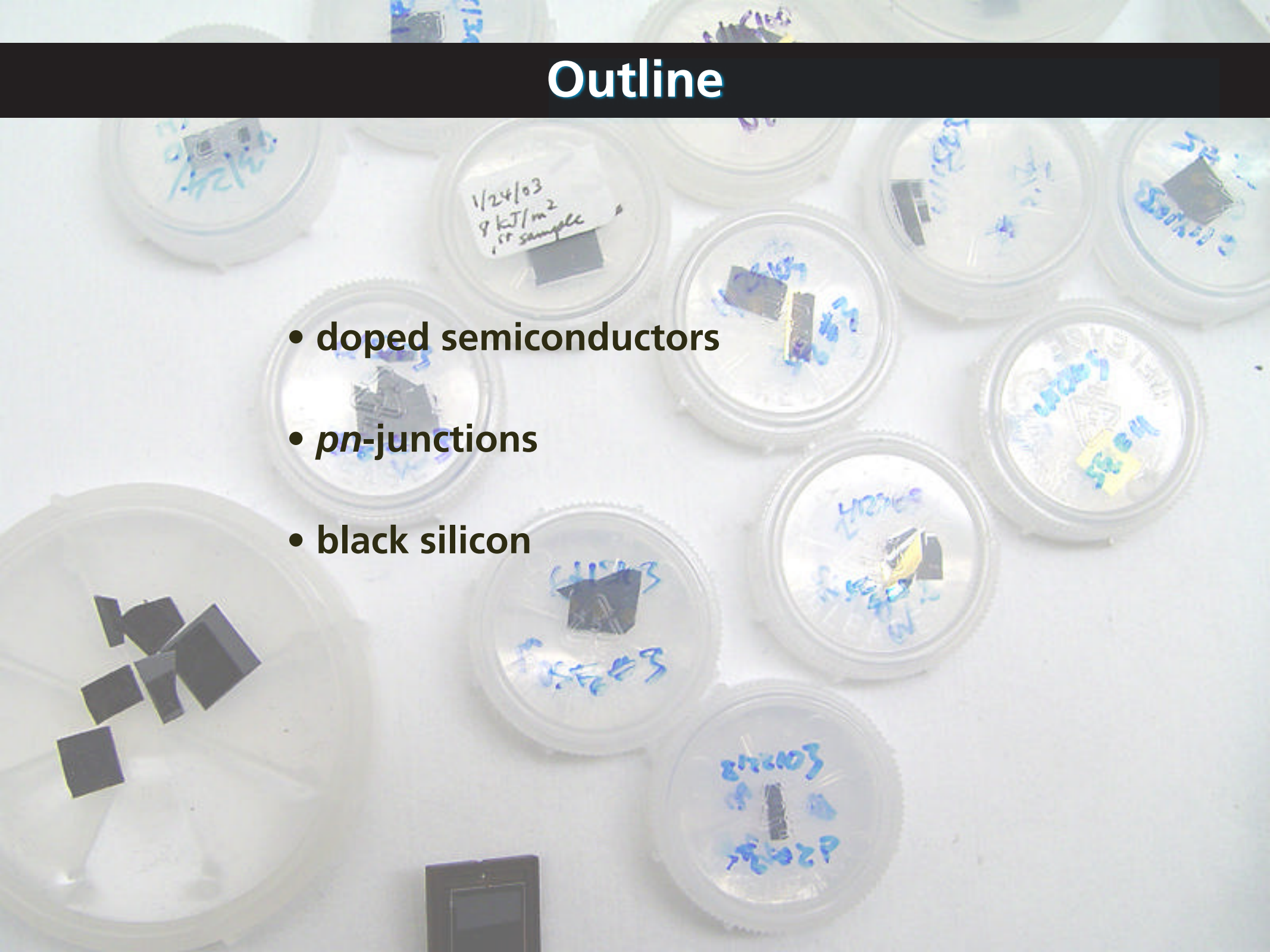
Introduction



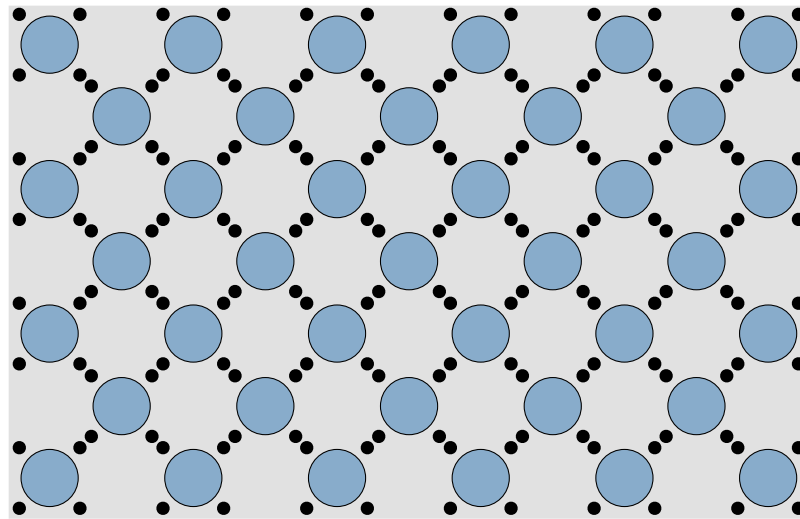
all electrons bound, so no conduction

Outline

- doped semiconductors
- *pn*-junctions
- black silicon

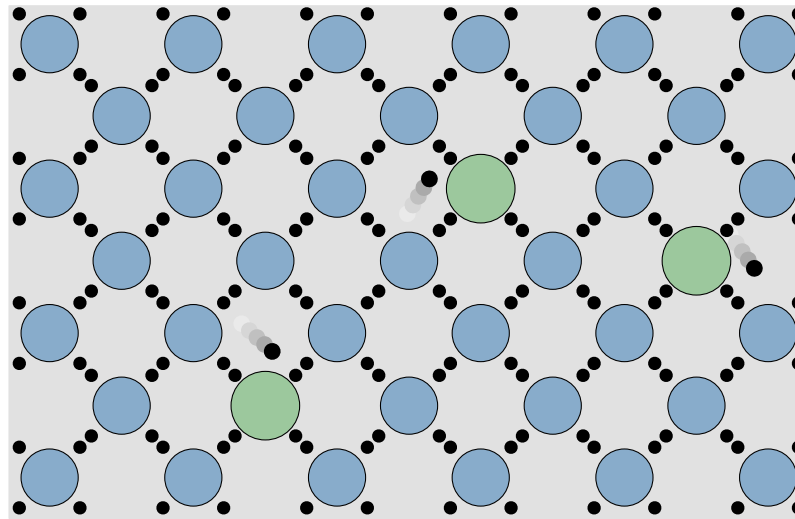


Doped semiconductors



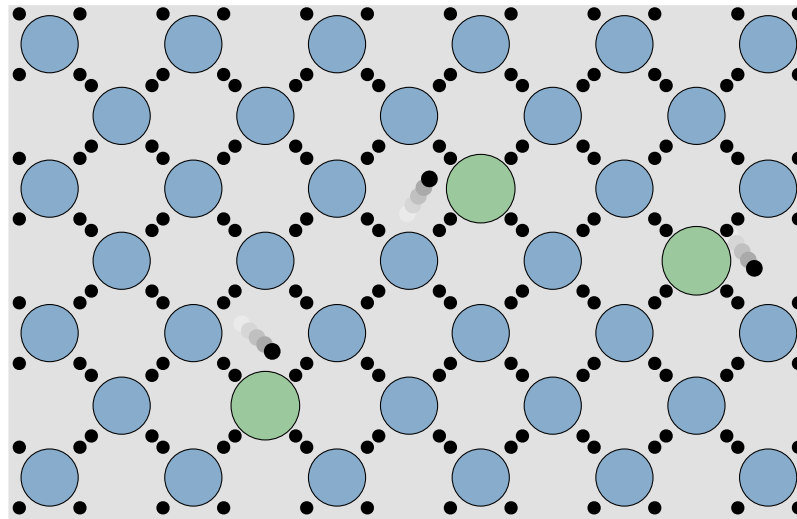
intrinsic silicon: no conduction

Doped semiconductors



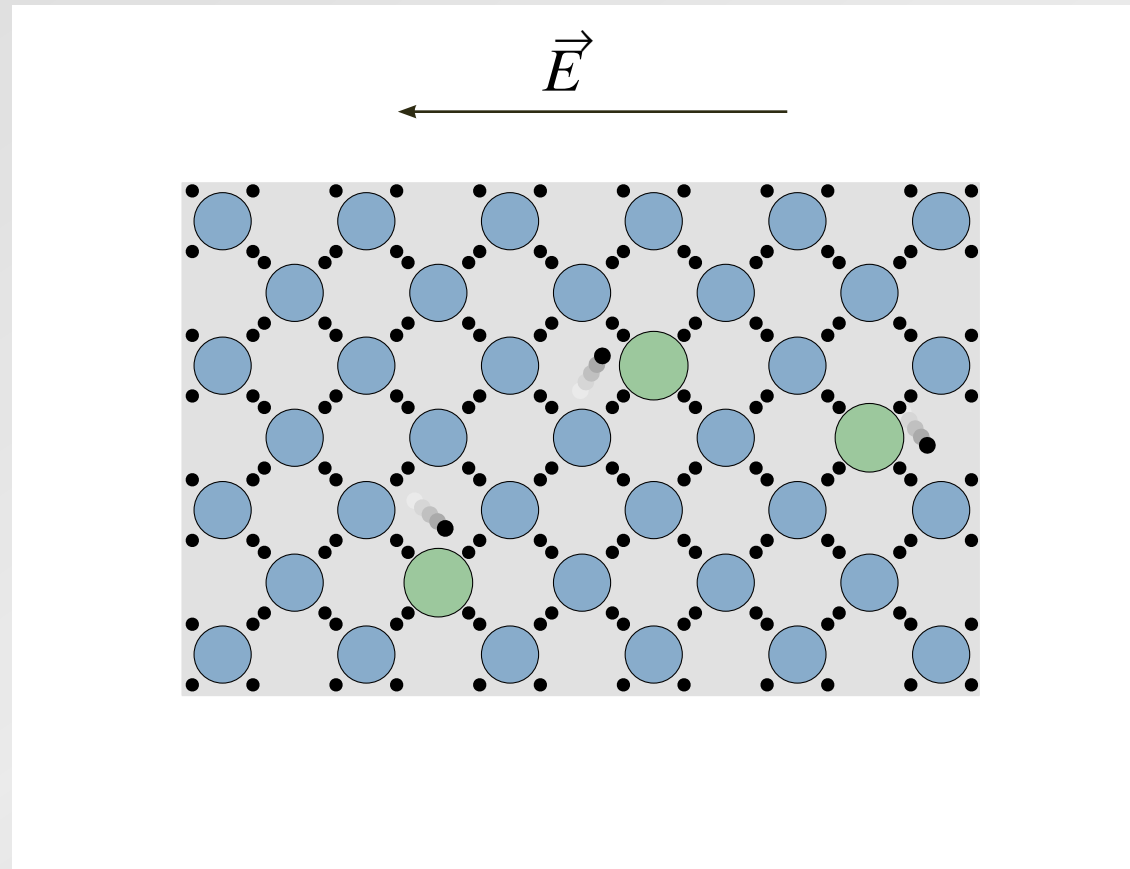
substitute phosphorous: surplus of (free) electrons

Doped semiconductors



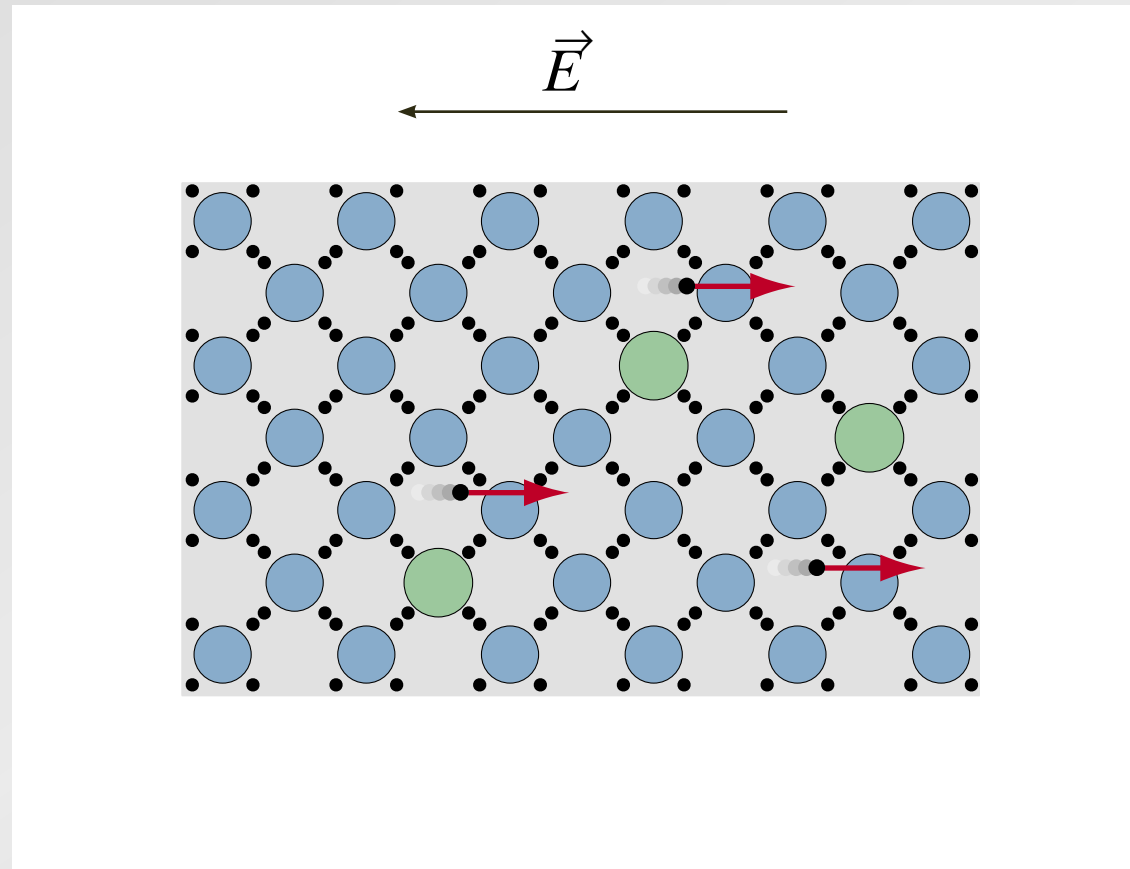
(but material as a whole still neutral!)

Doped semiconductors



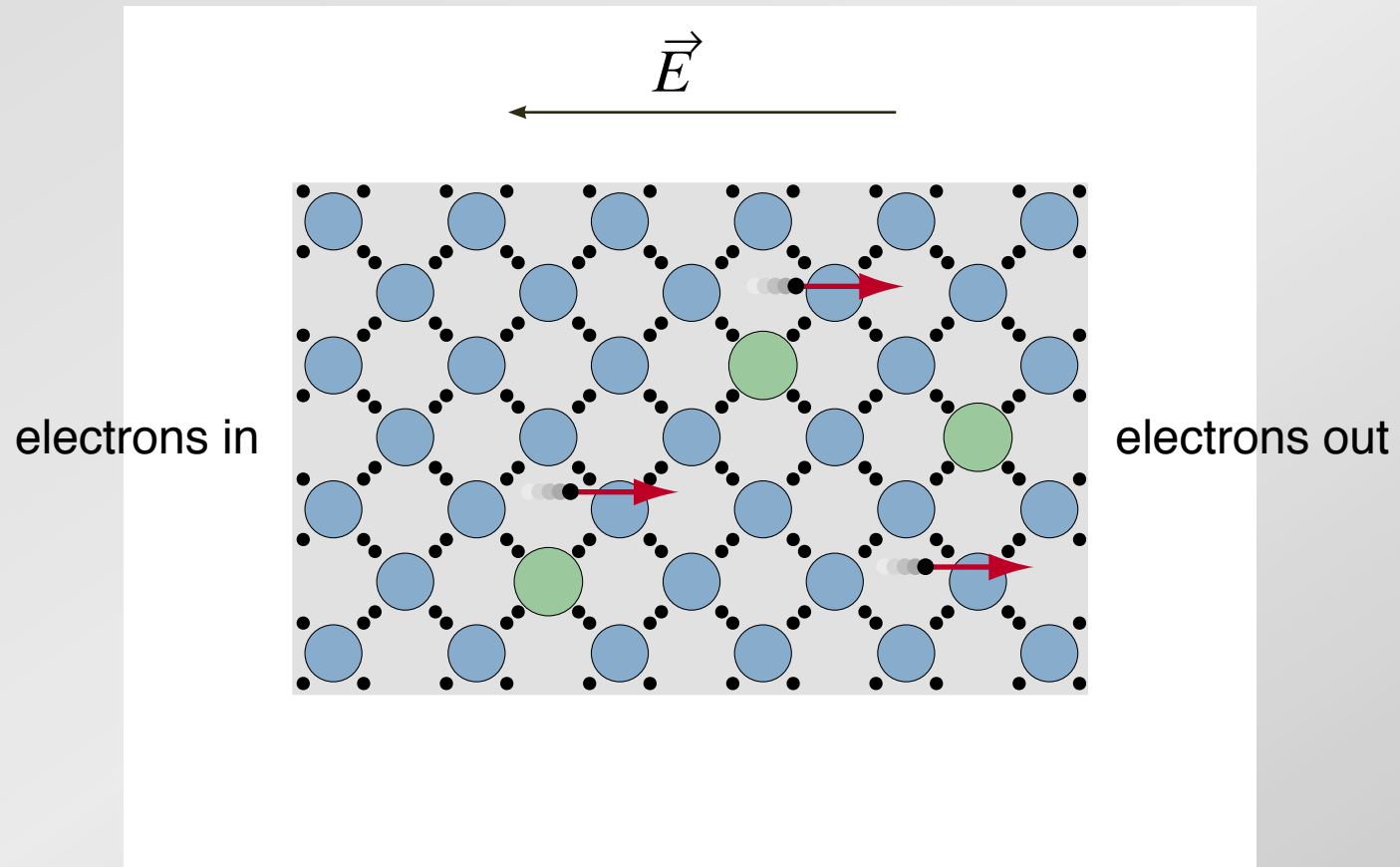
apply electric field...

Doped semiconductors



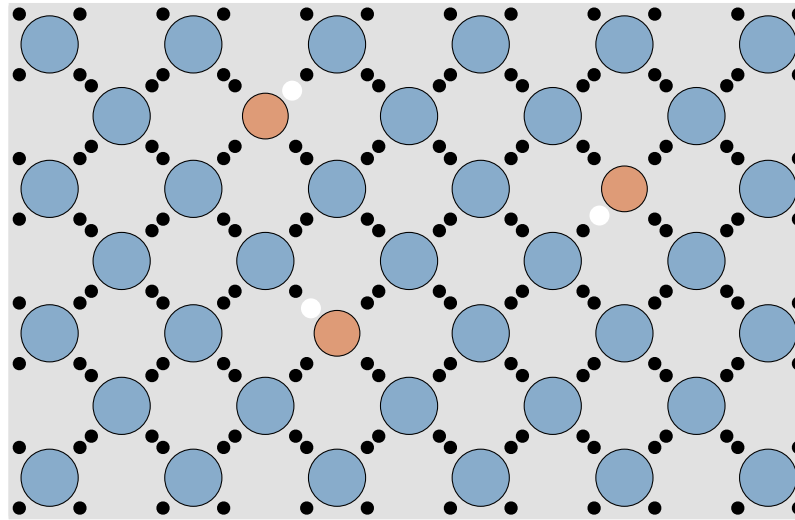
...free electrons lead to conduction

Doped semiconductors



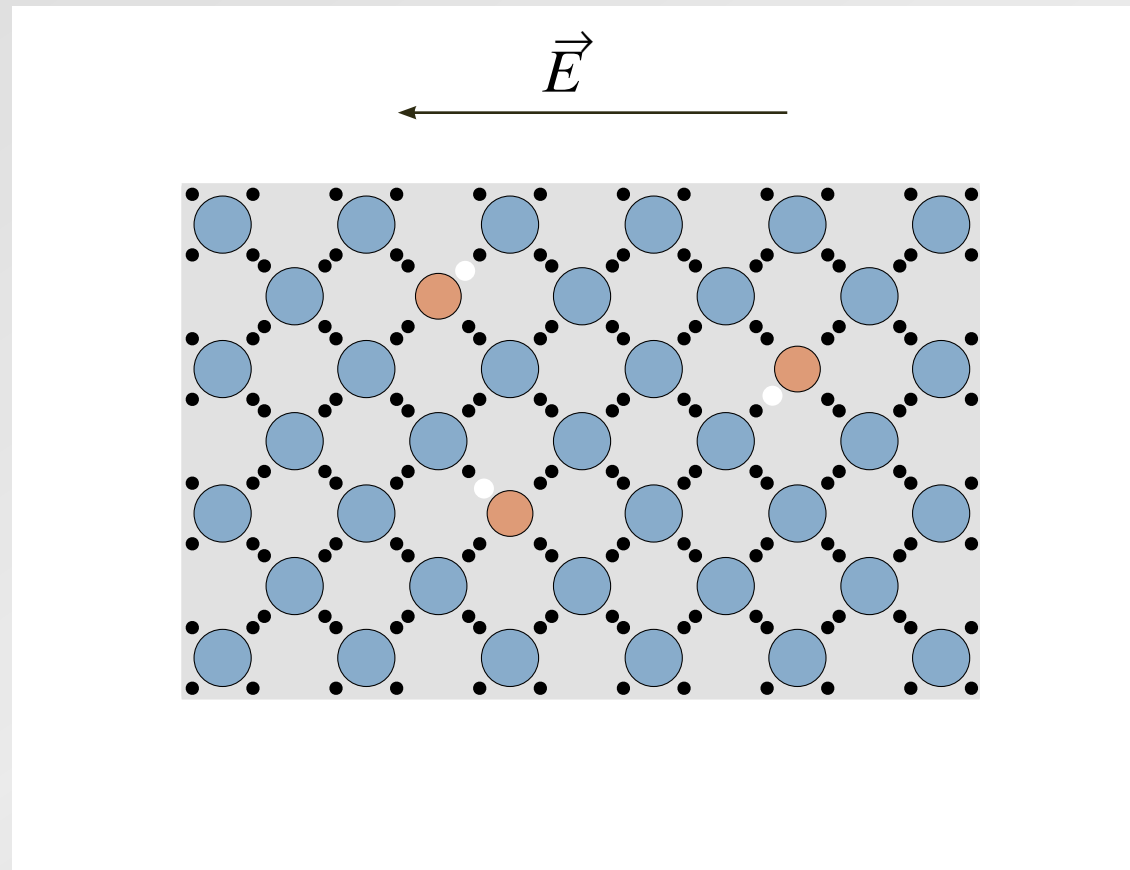
...free electrons lead to conduction

Doped semiconductors



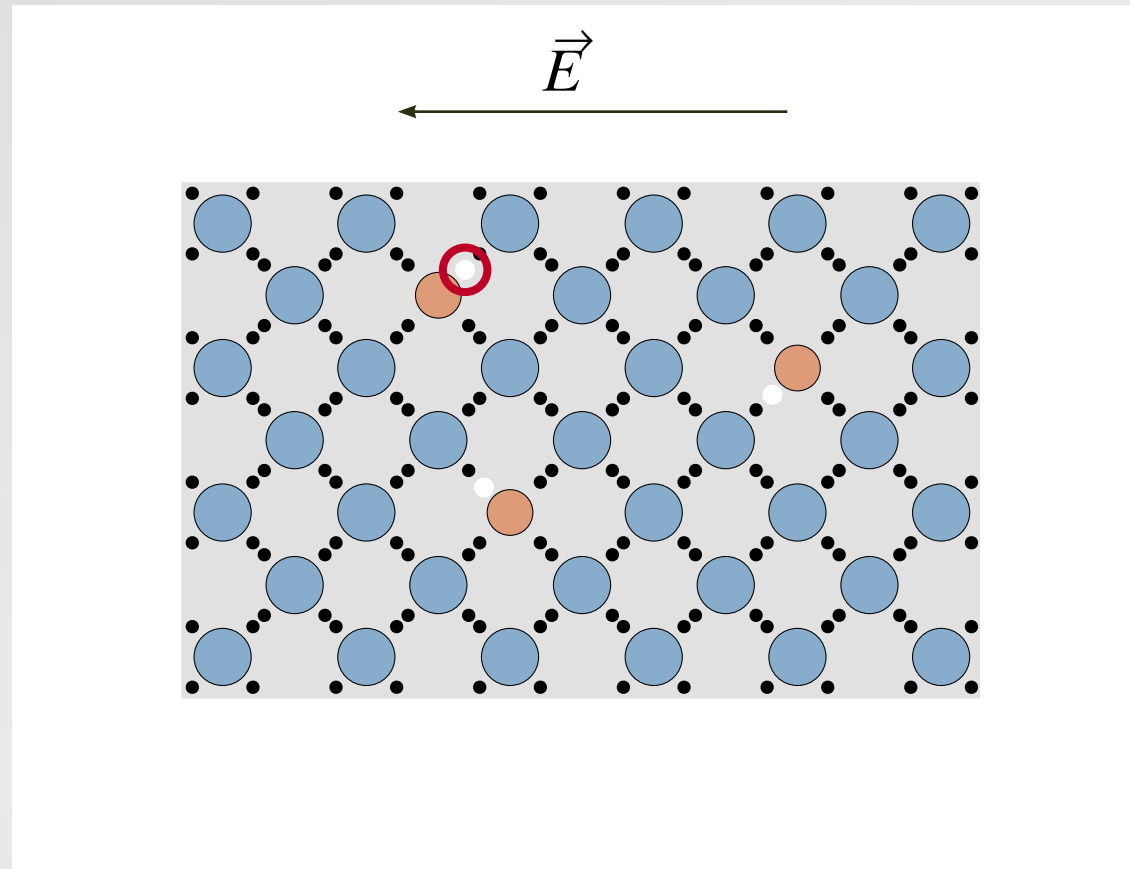
substitute boron: deficit of electrons leaves "holes"

Doped semiconductors



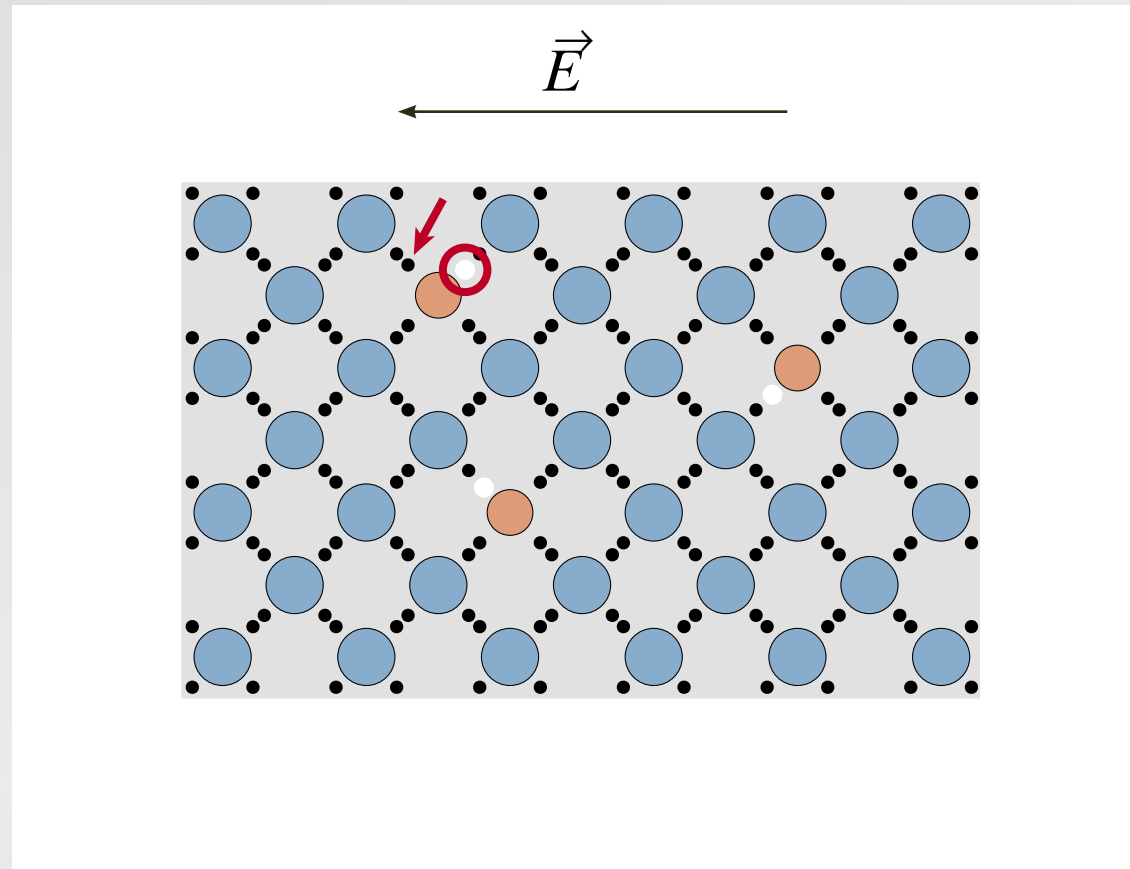
apply electric field...

Doped semiconductors



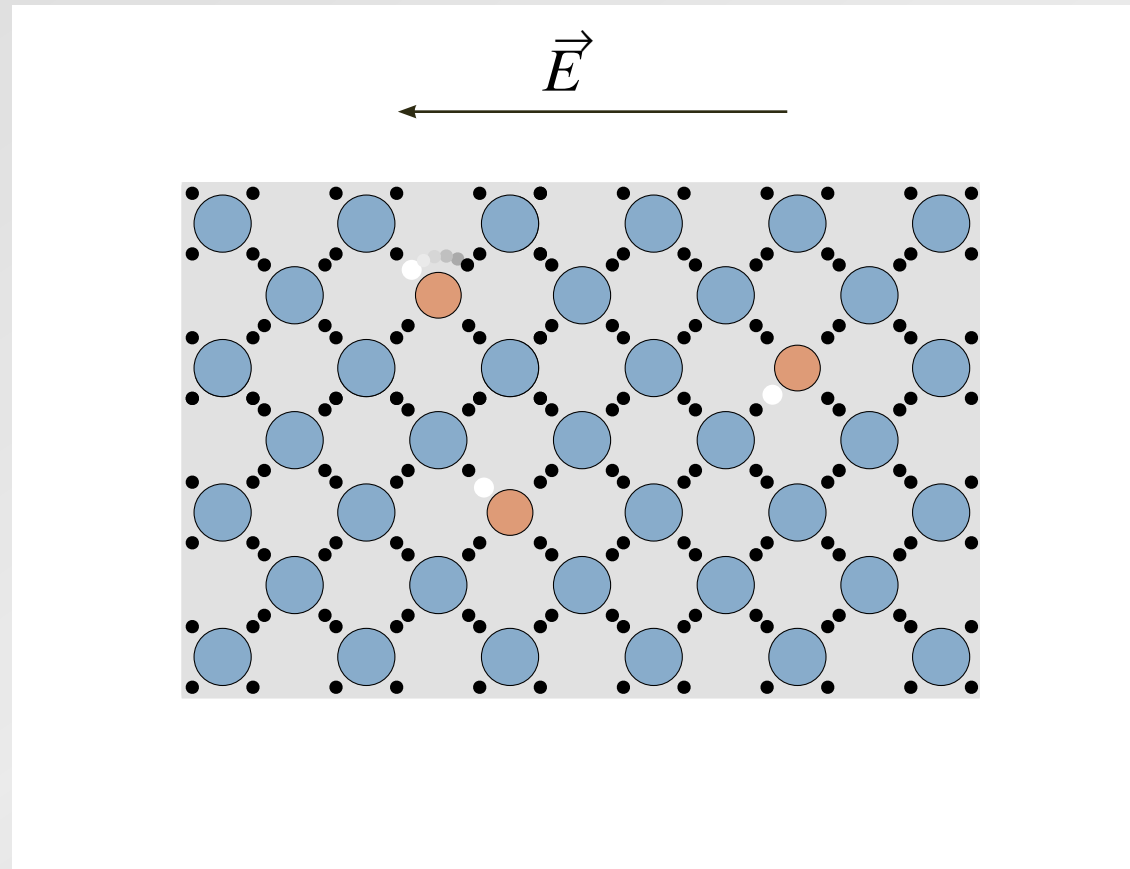
...presence of holes leads to conduction

Doped semiconductors



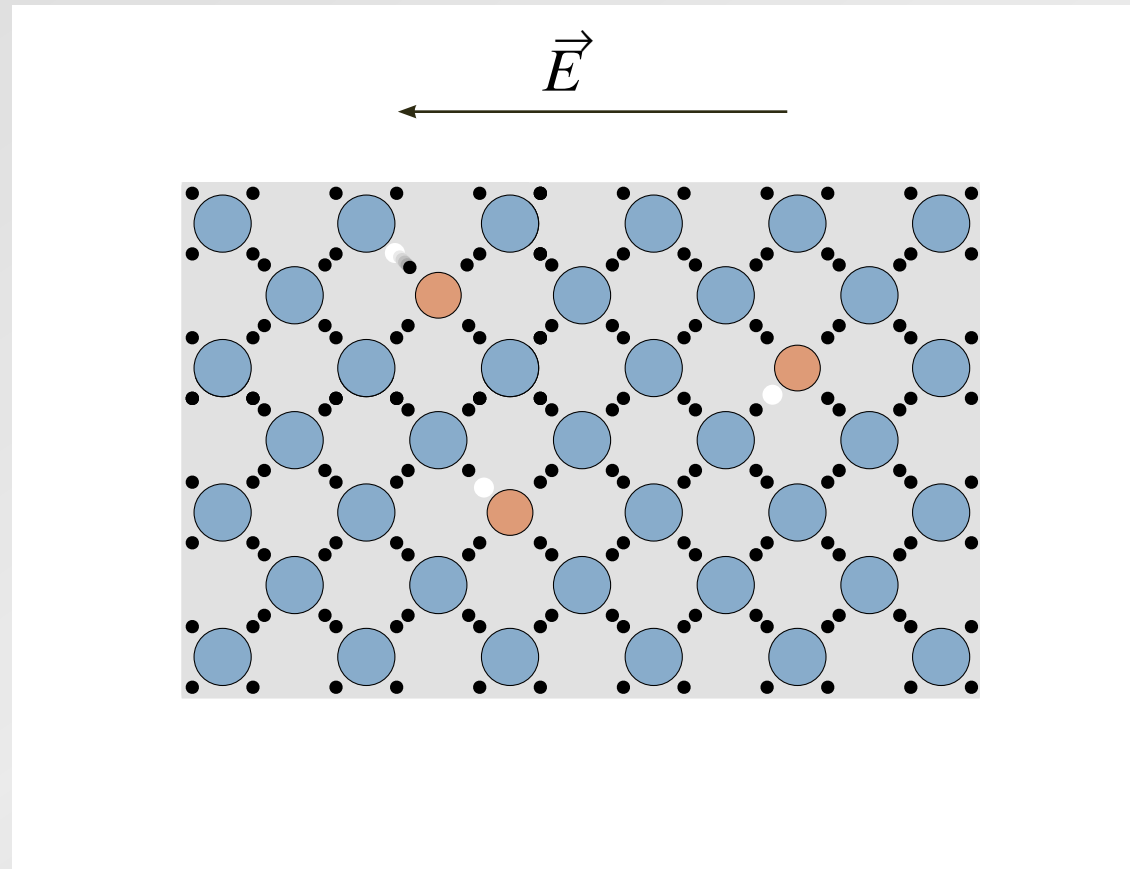
...presence of holes leads to conduction

Doped semiconductors



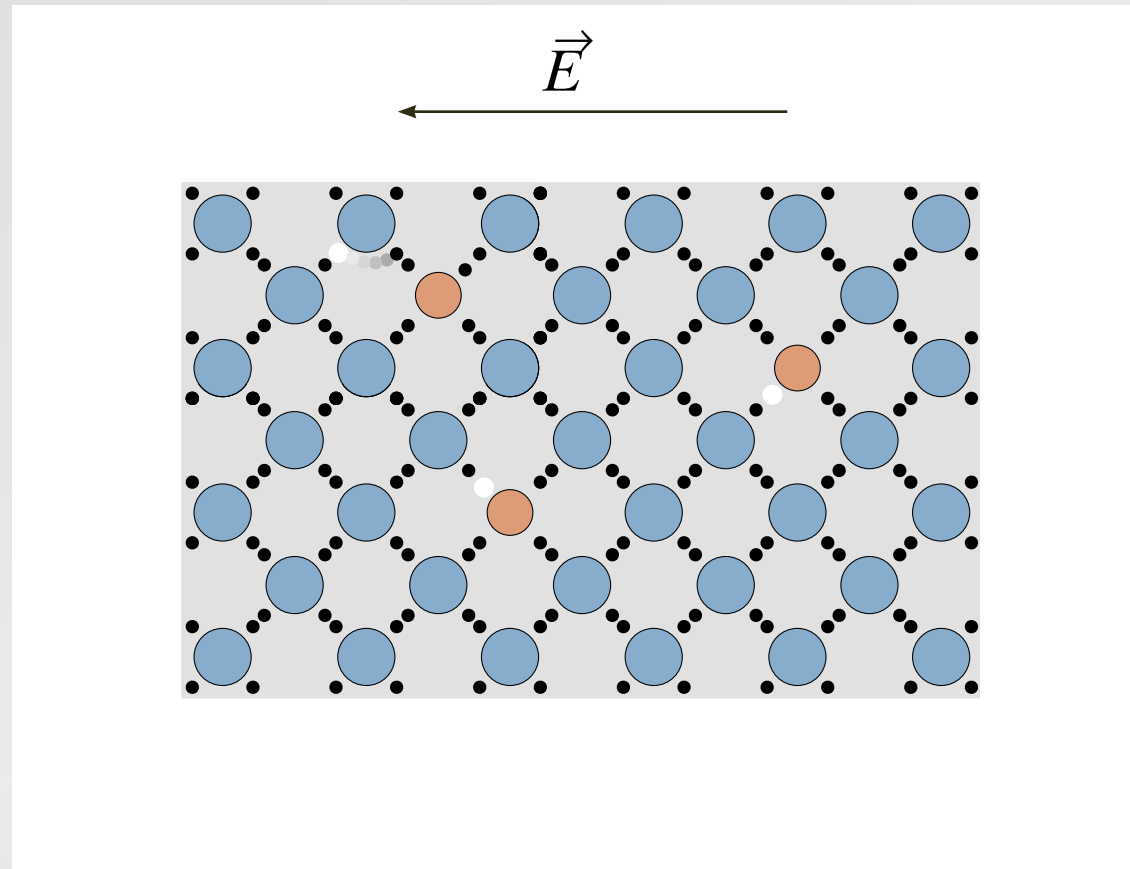
...presence of holes leads to conduction

Doped semiconductors



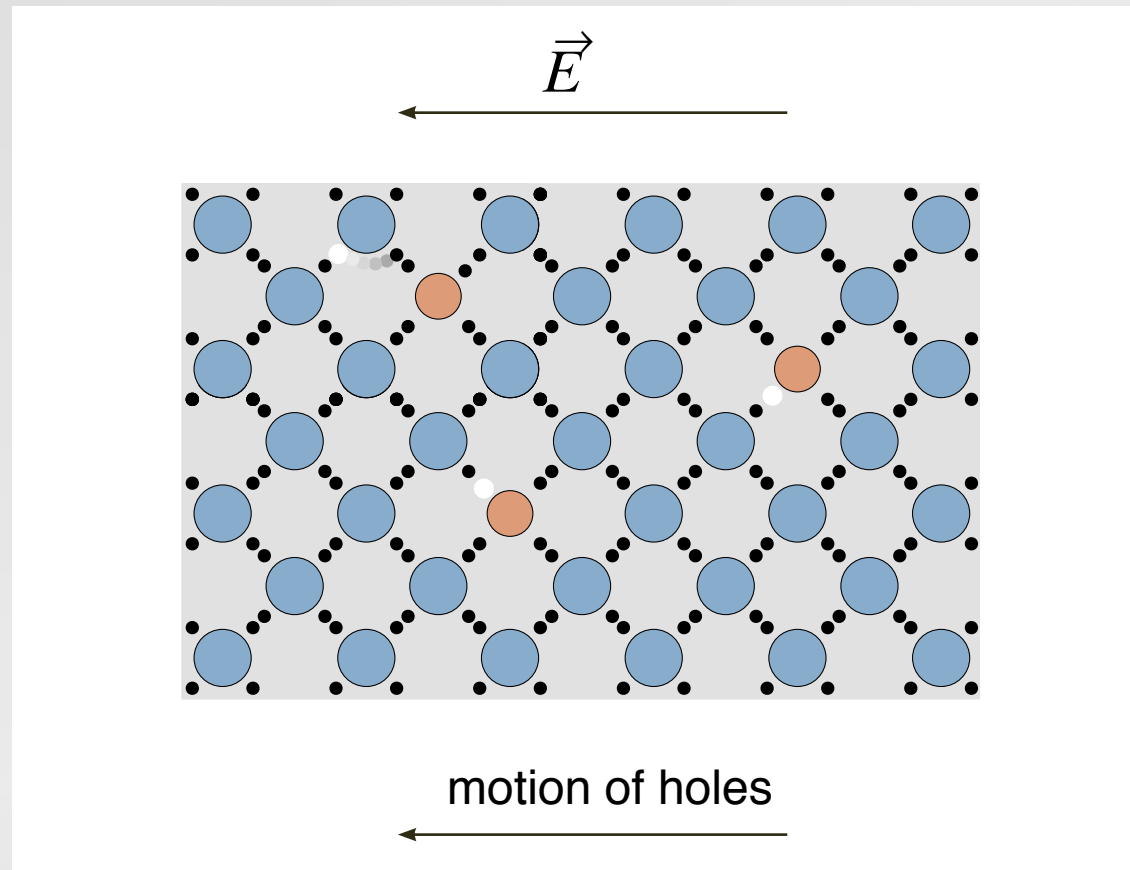
...presence of holes leads to conduction

Doped semiconductors



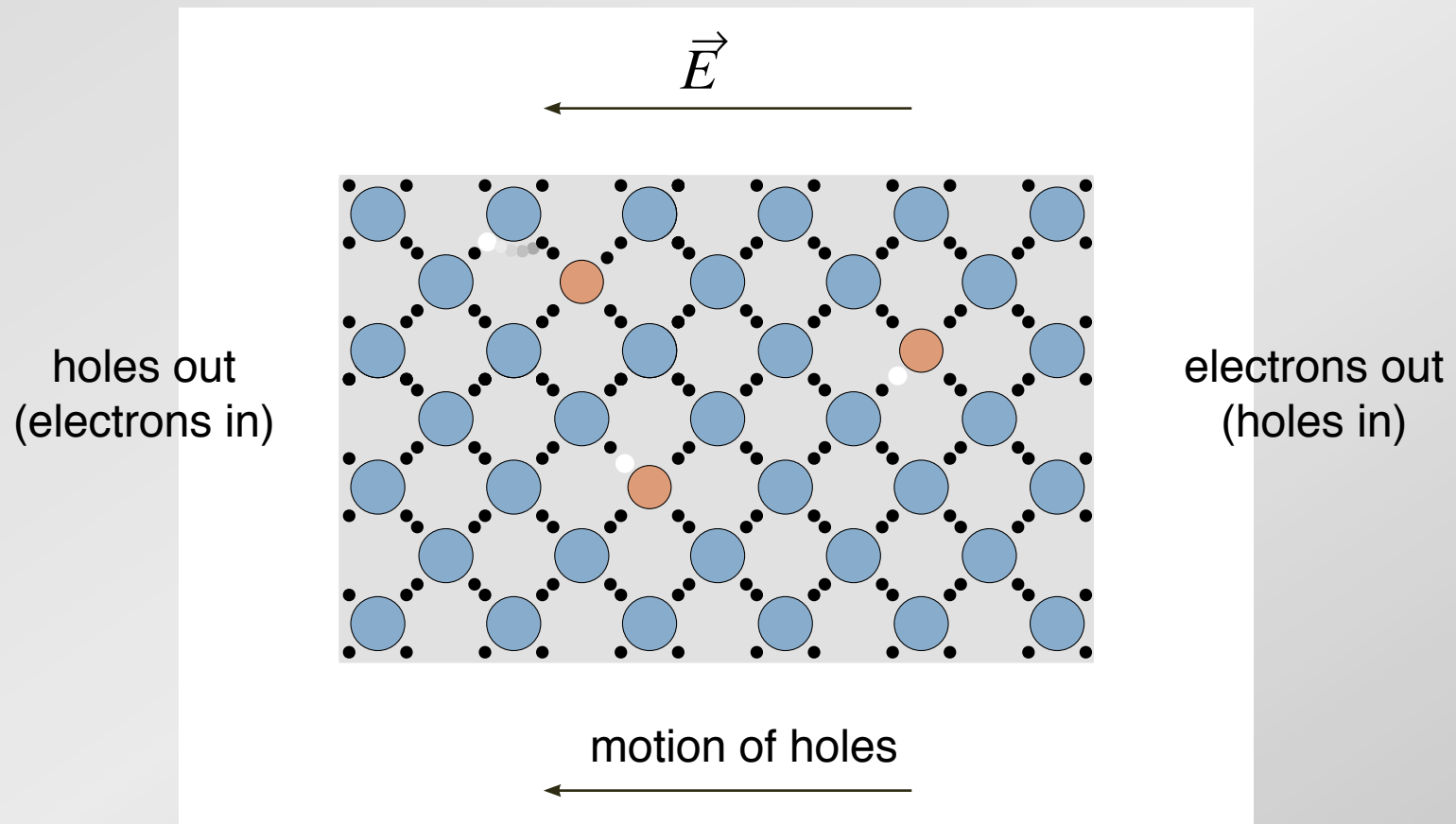
...presence of holes leads to conduction

Doped semiconductors



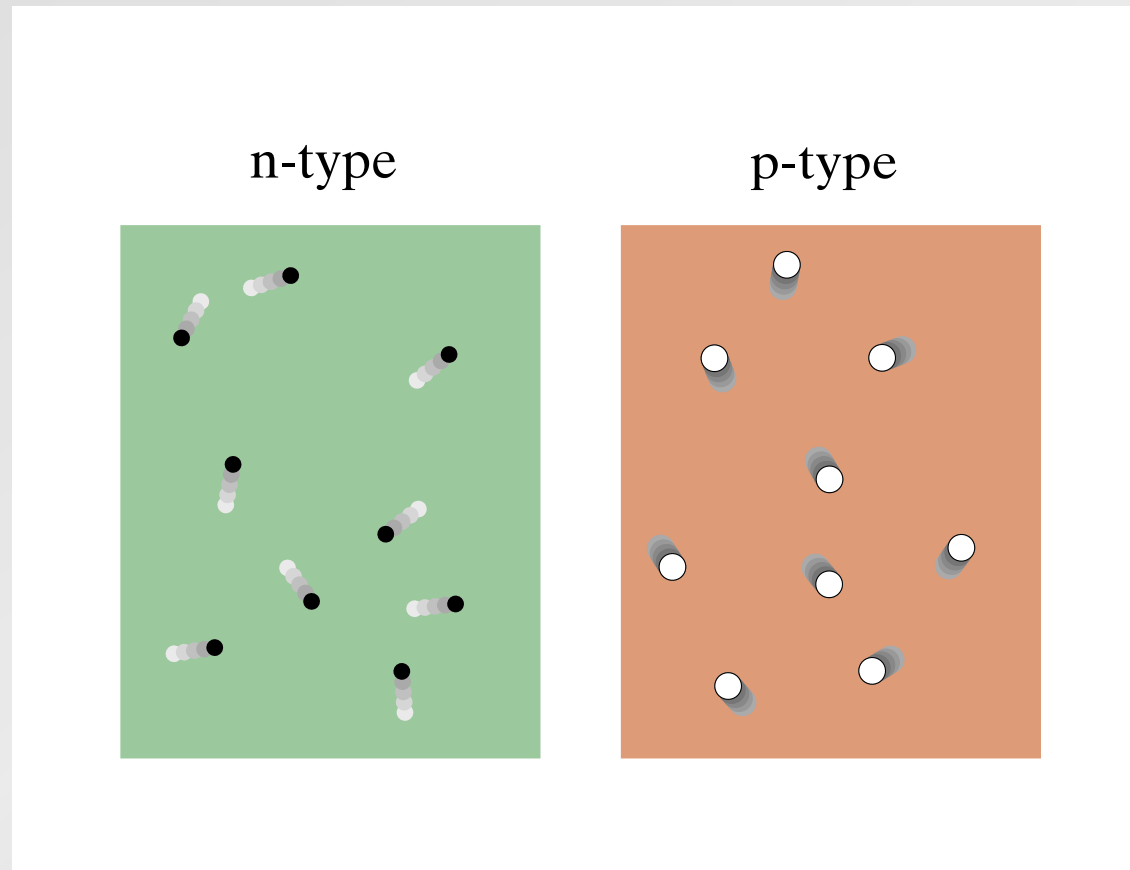
holes are like positively charged particles

Doped semiconductors

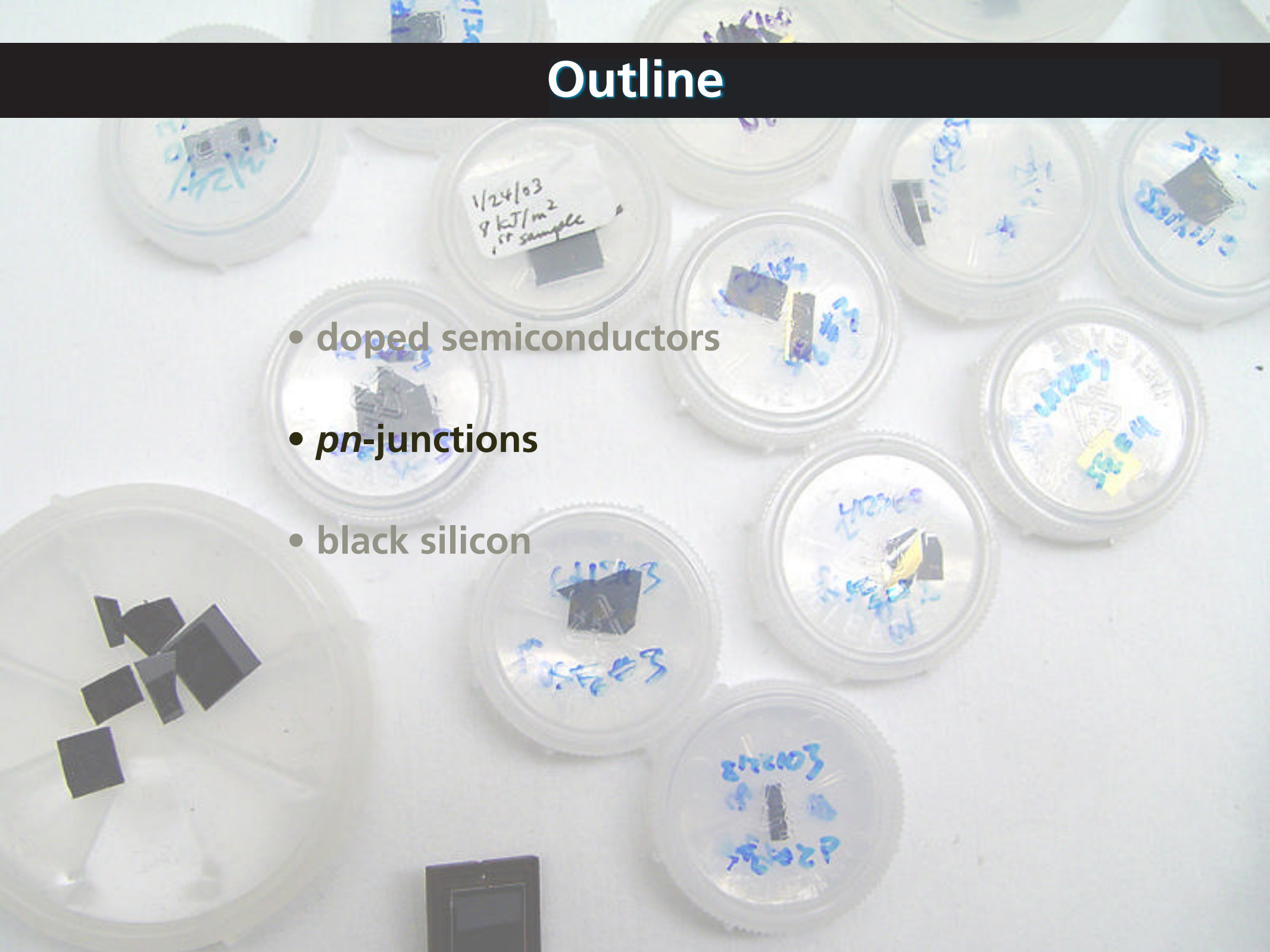


holes are like positively charged particles

Doped semiconductors

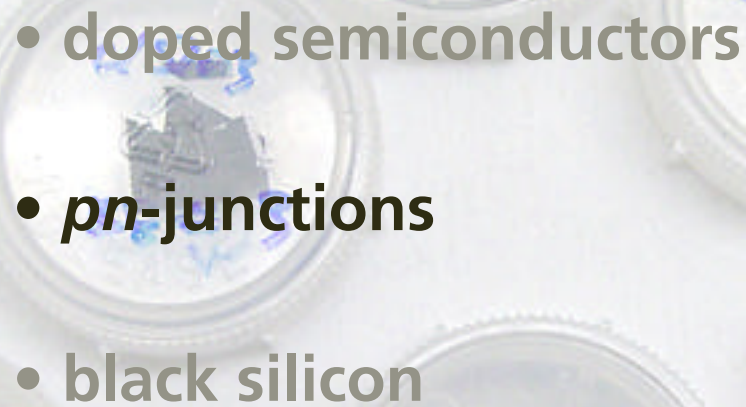


simplify representation



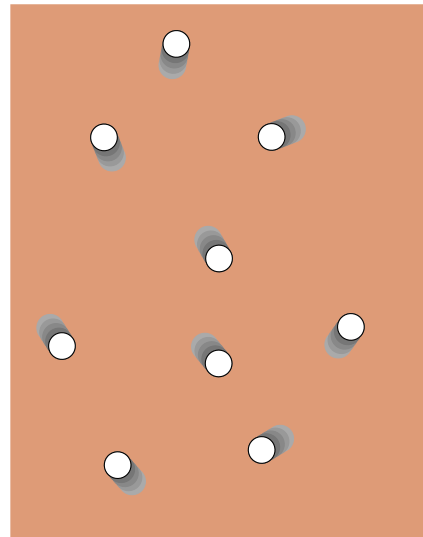
Outline

- doped semiconductors
- *pn*-junctions
- black silicon

- 
- doped semiconductors
 - *pn*-junctions
 - black silicon

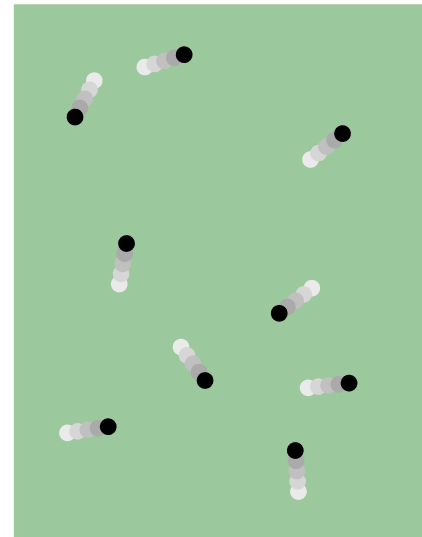
pn-junctions

neutral



p-type

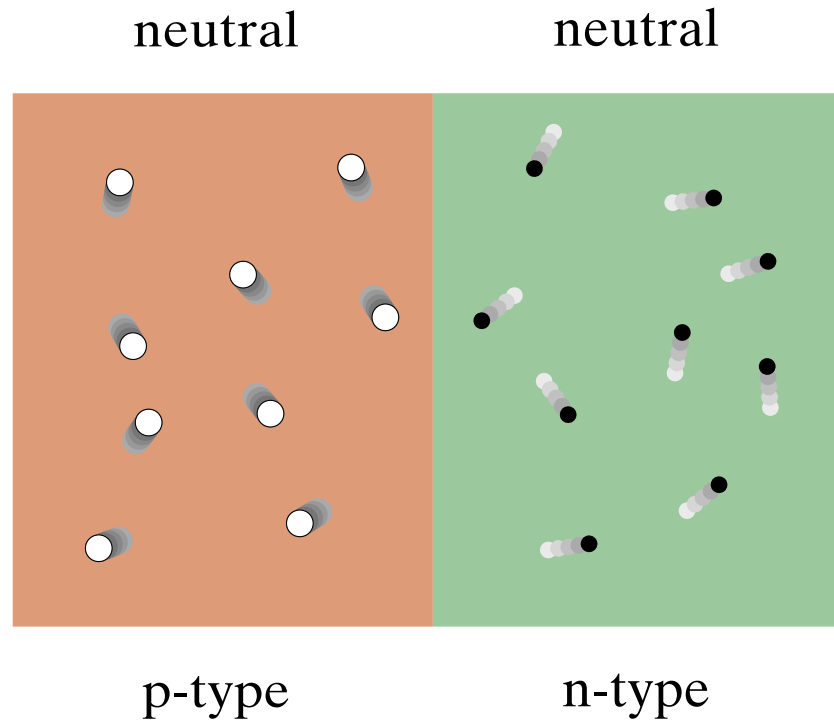
neutral



n-type

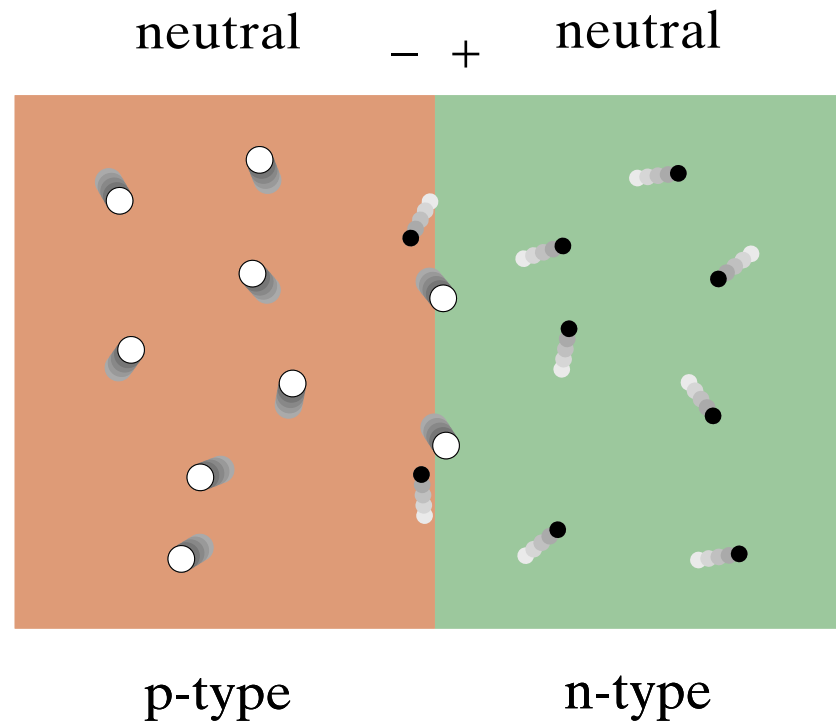
bring *p* and *n* materials together...

pn-junctions



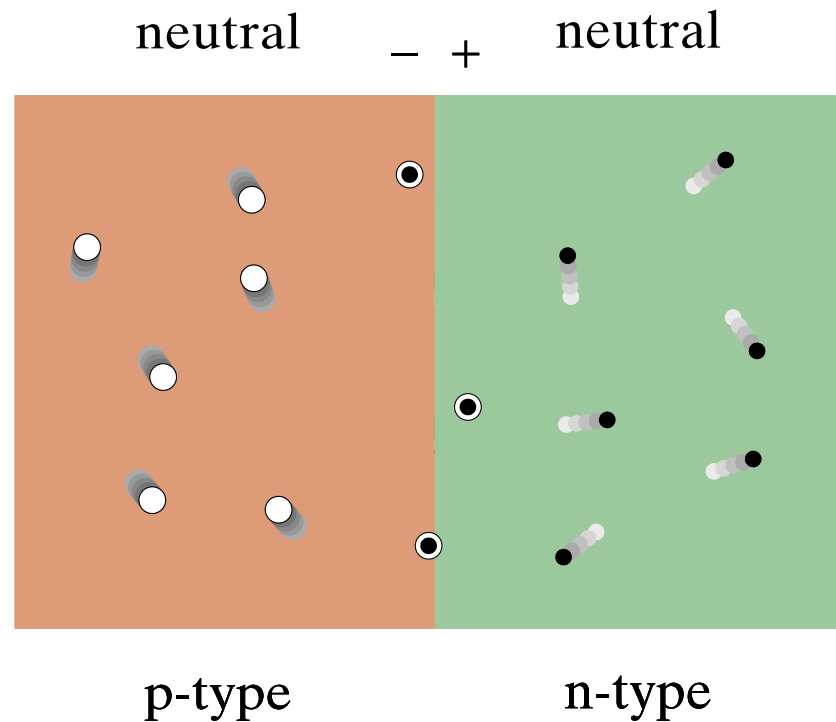
bring *p* and *n* materials together...

pn-junctions



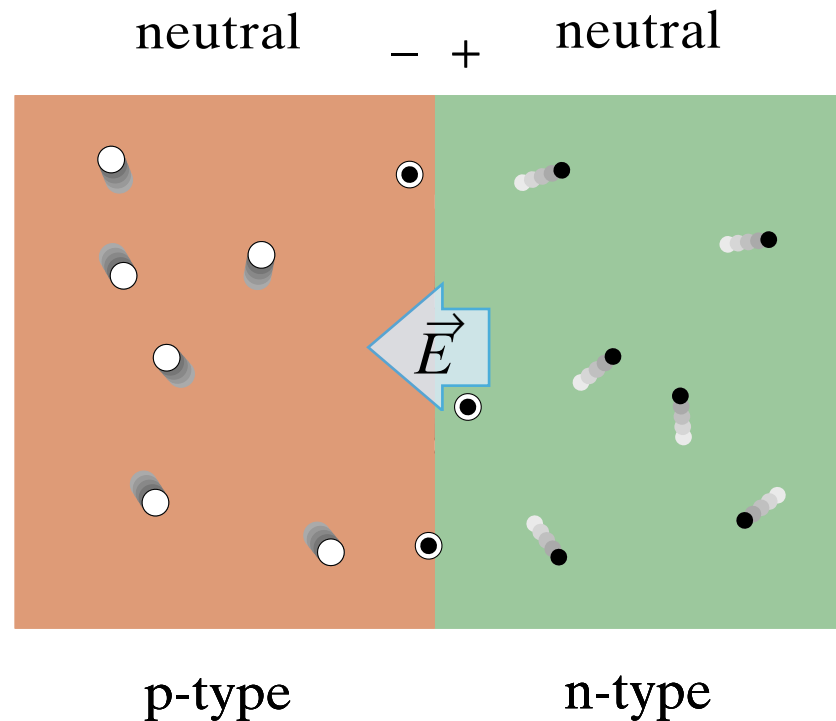
electrons and holes diffuse across junction...

pn-junctions



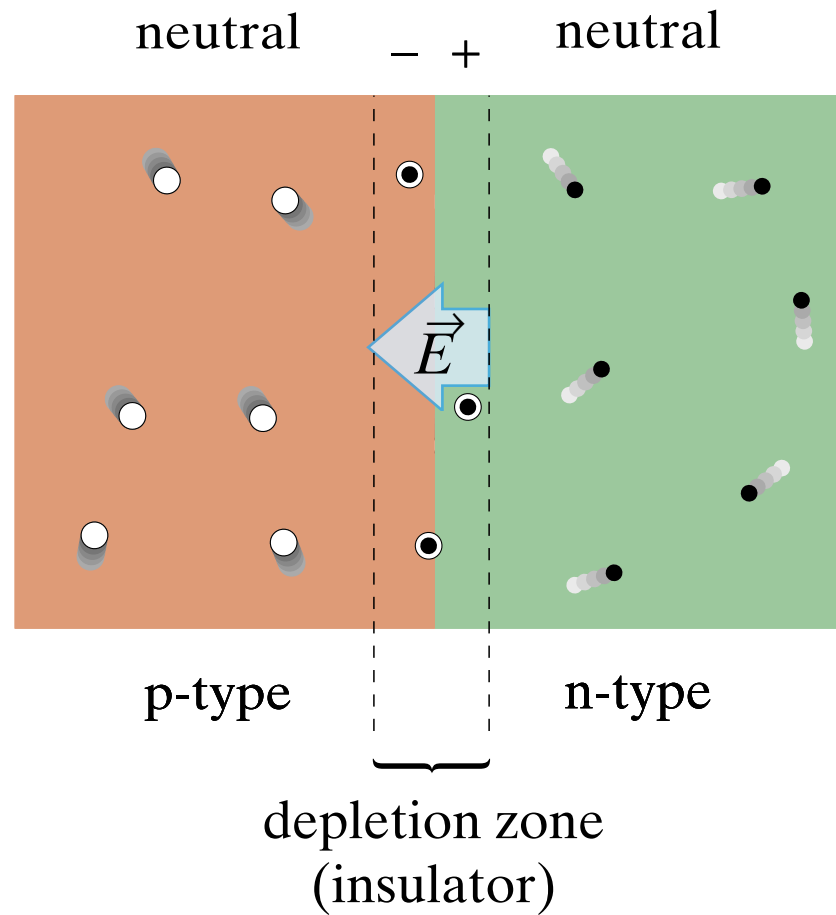
...and get 'trapped' after they combine

pn-junctions



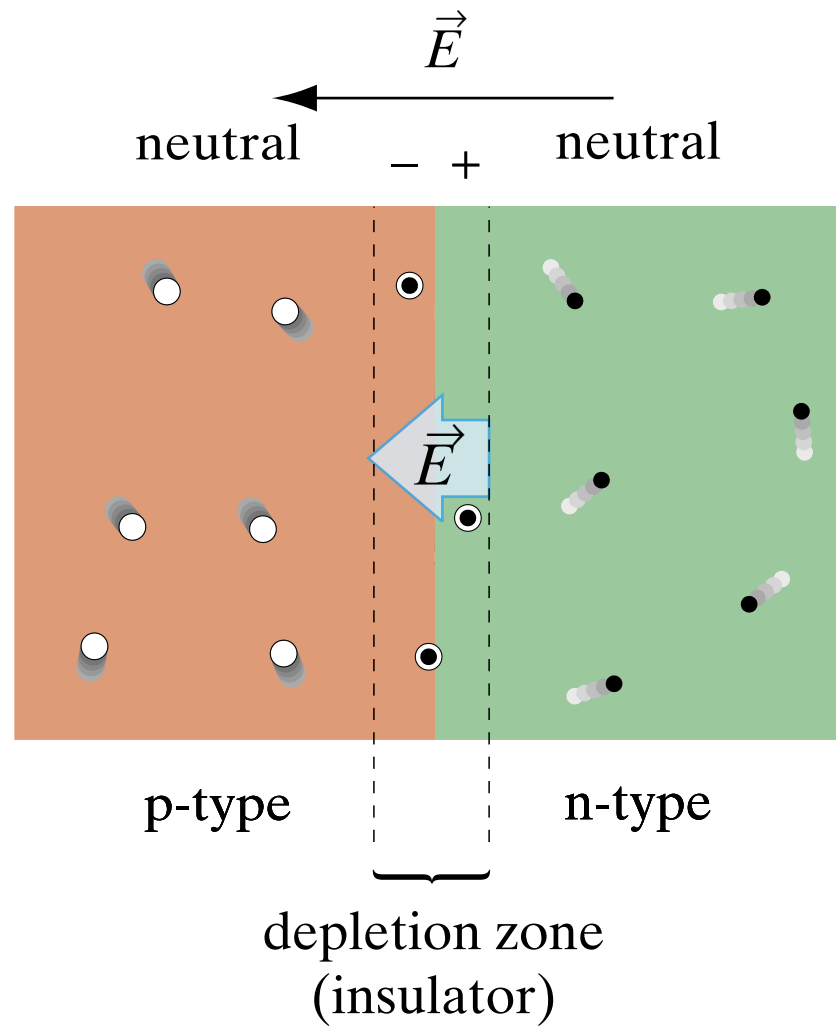
build-up of charge leads to electric field that stops diffusion

pn-junctions



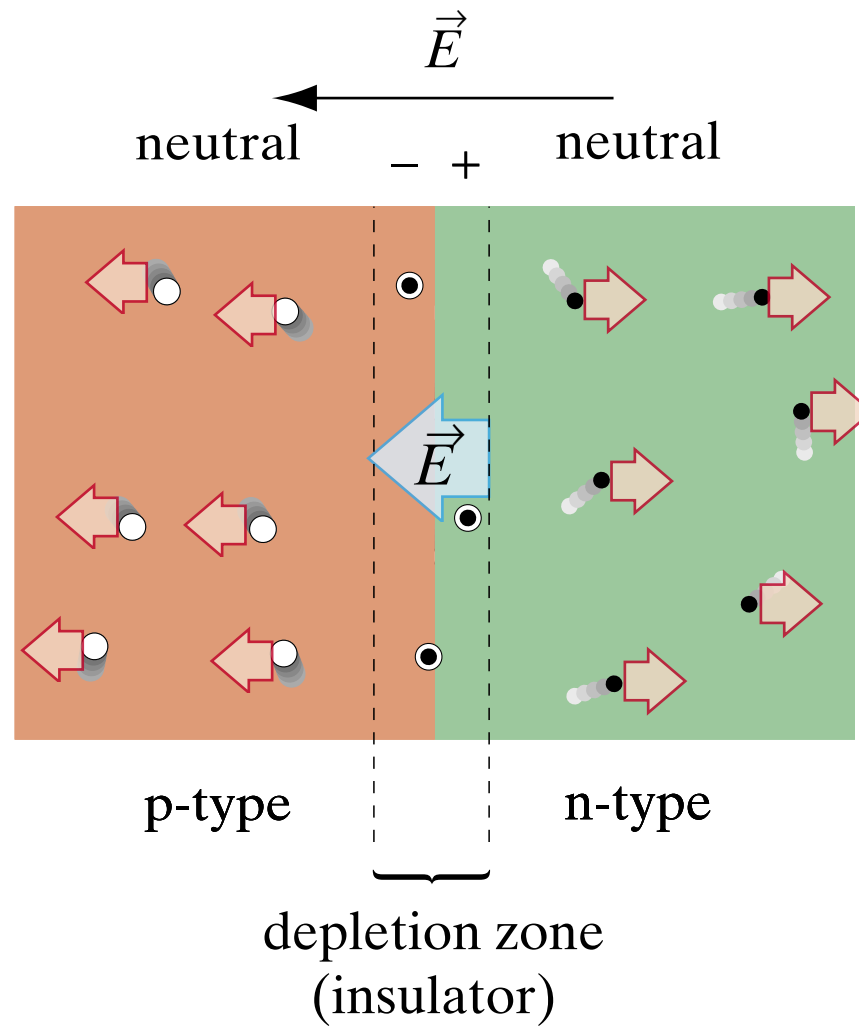
non-conducting layer at junction

pn-junctions



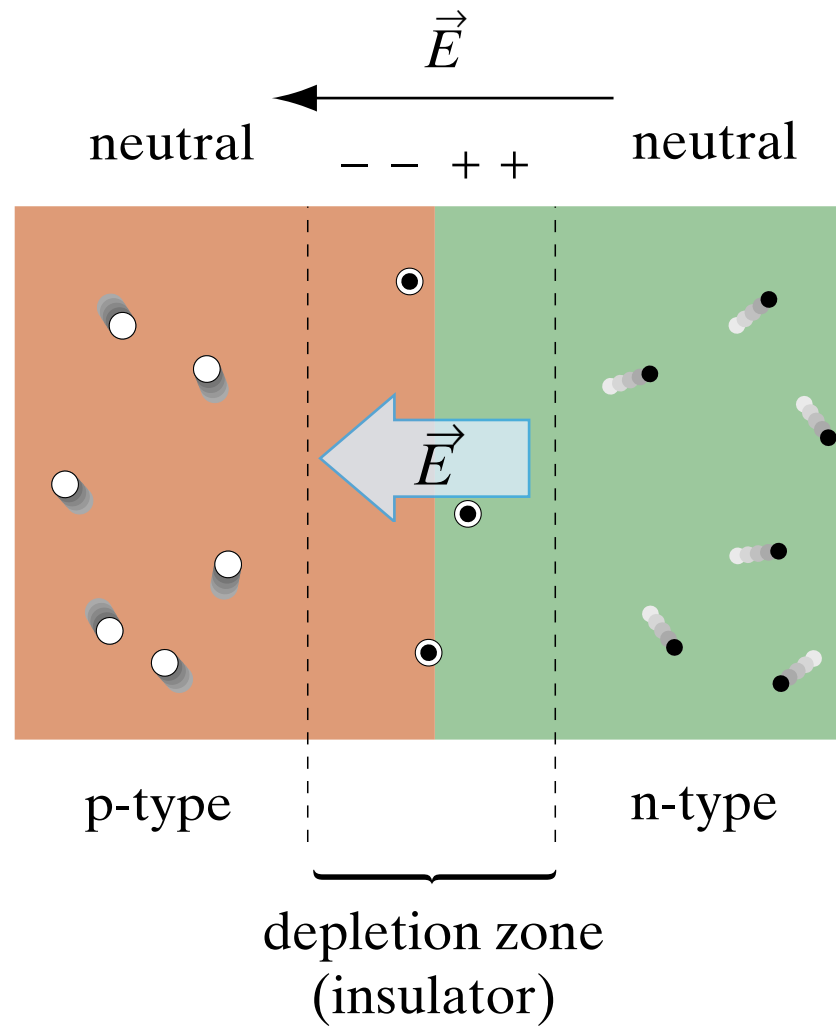
apply electric field...

pn-junctions



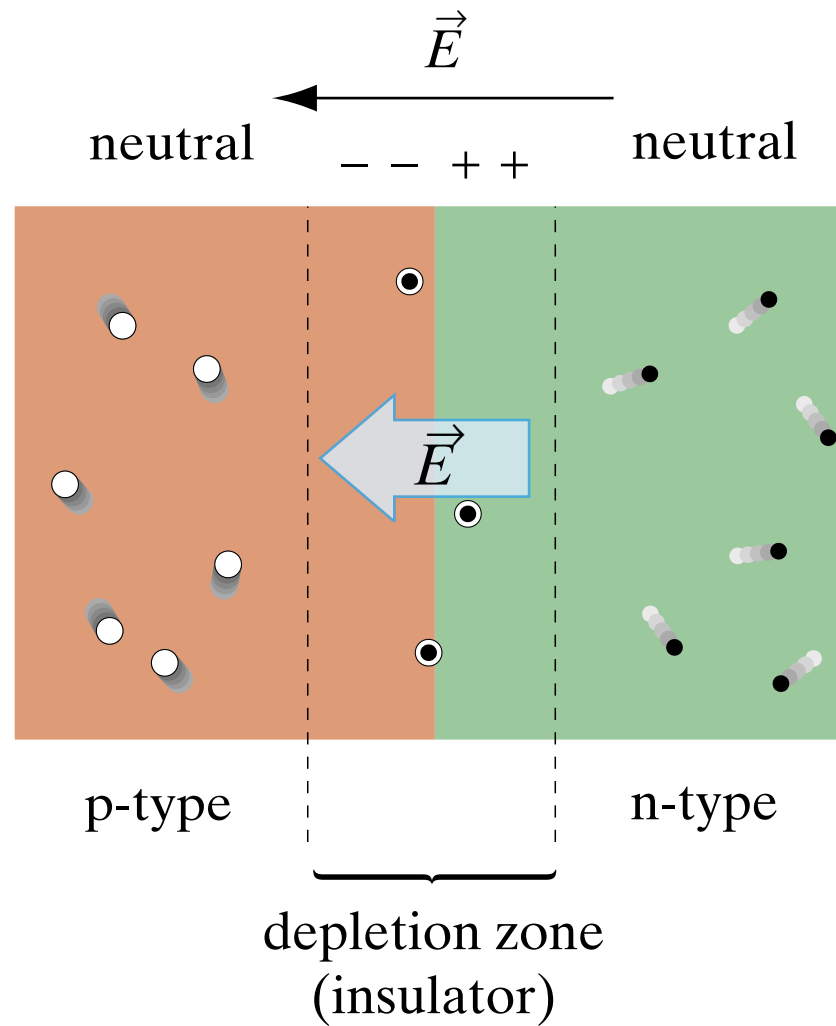
...holes pushed to left, electrons to right...

pn-junctions



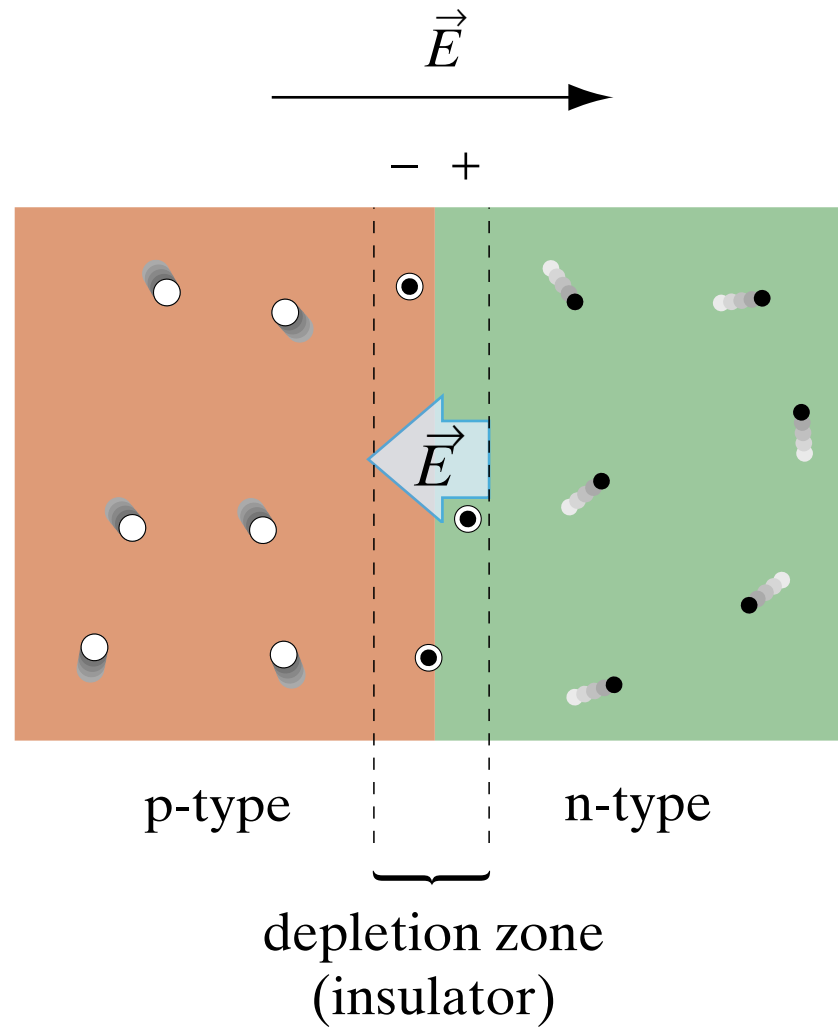
...and so depletion zone expands

pn-junctions



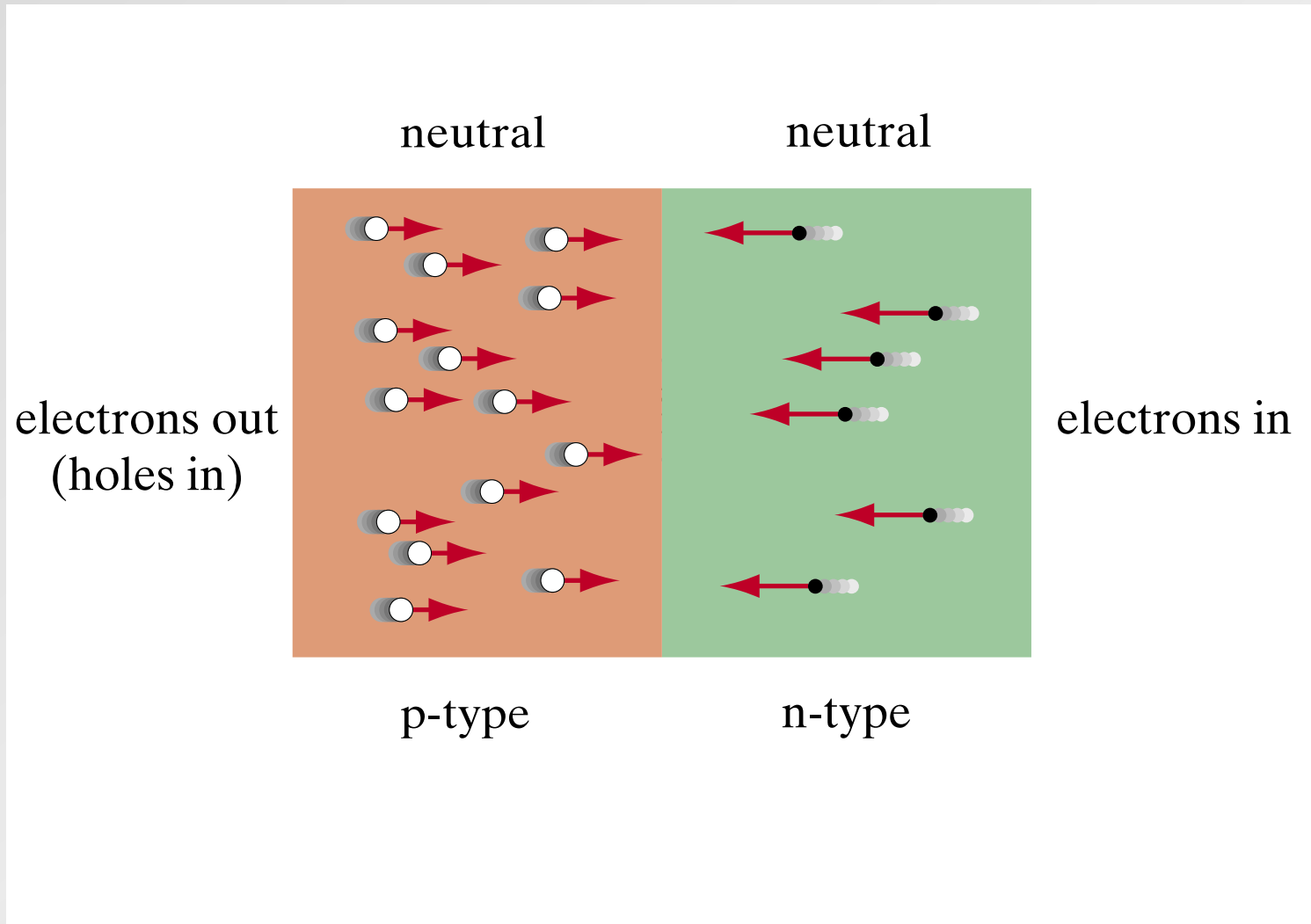
NO conduction

pn-junctions



reverse electric field...

pn-junctions



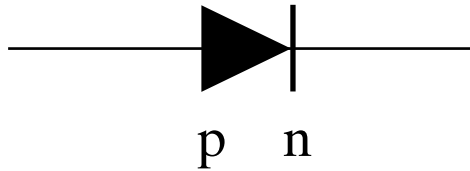
...depletion zone shrinks and current flows

pn-junctions

so *pn*-junction like one-way valve for charge flow

pn-junctions

diode

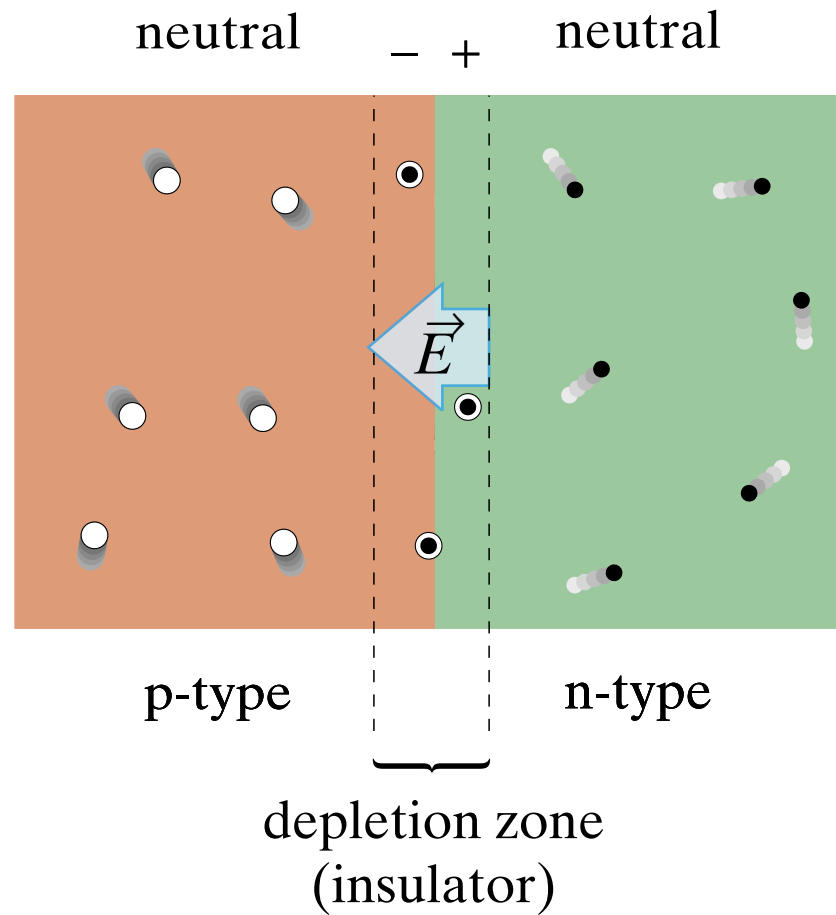


current flows along arrow only (from *p* to *n*)

pn-junctions

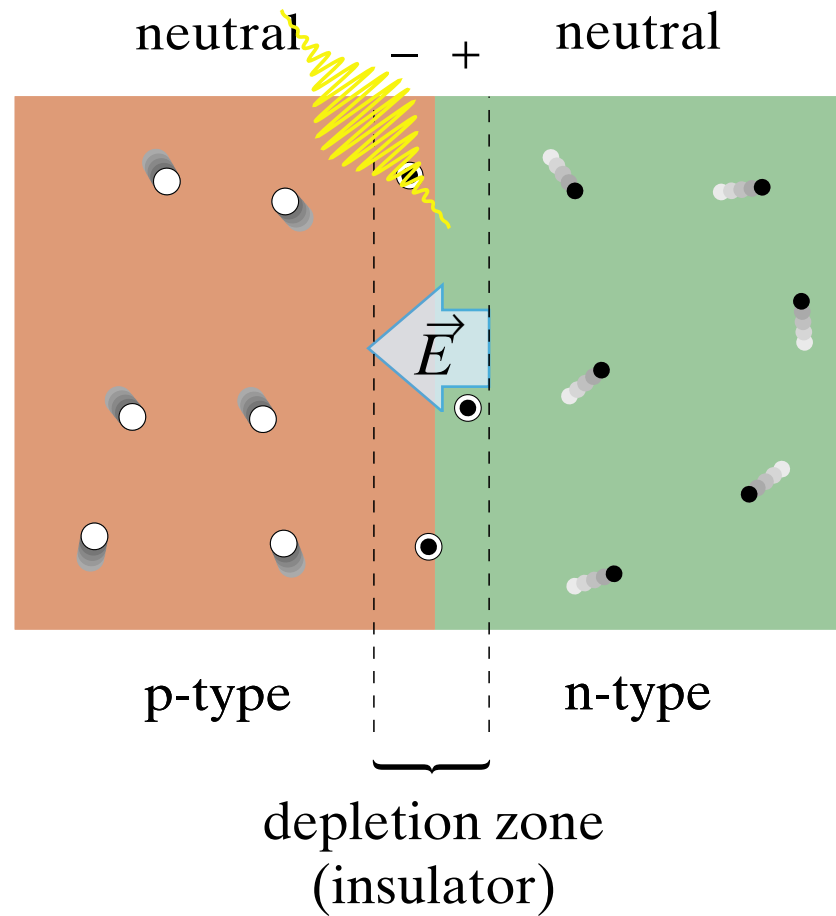
can also be used as a light detector!

pn-junctions



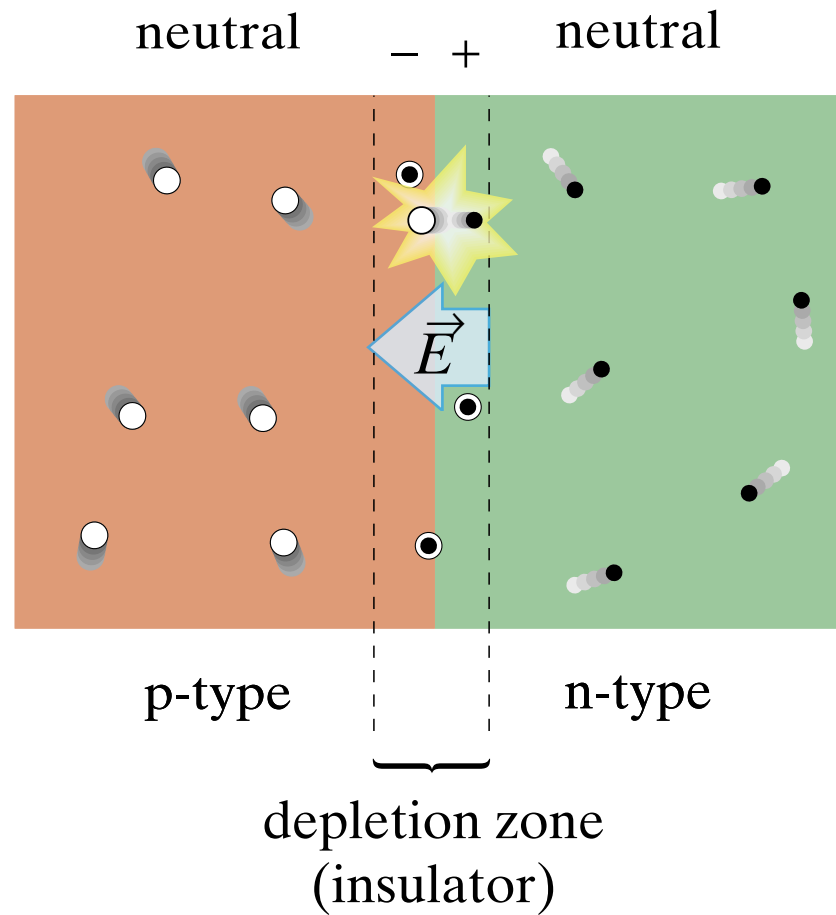
depletion layer can convert light into electric energy

pn-junctions



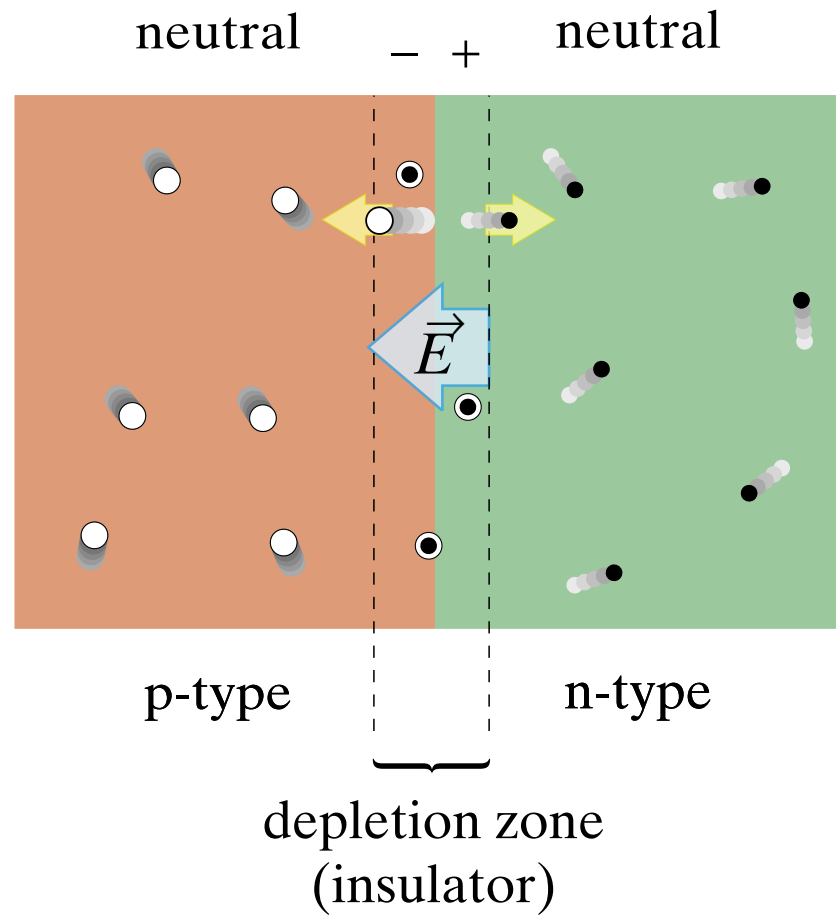
incident photon knocks out electron...

pn-junctions



...creating an electron-hole pair

pn-junctions

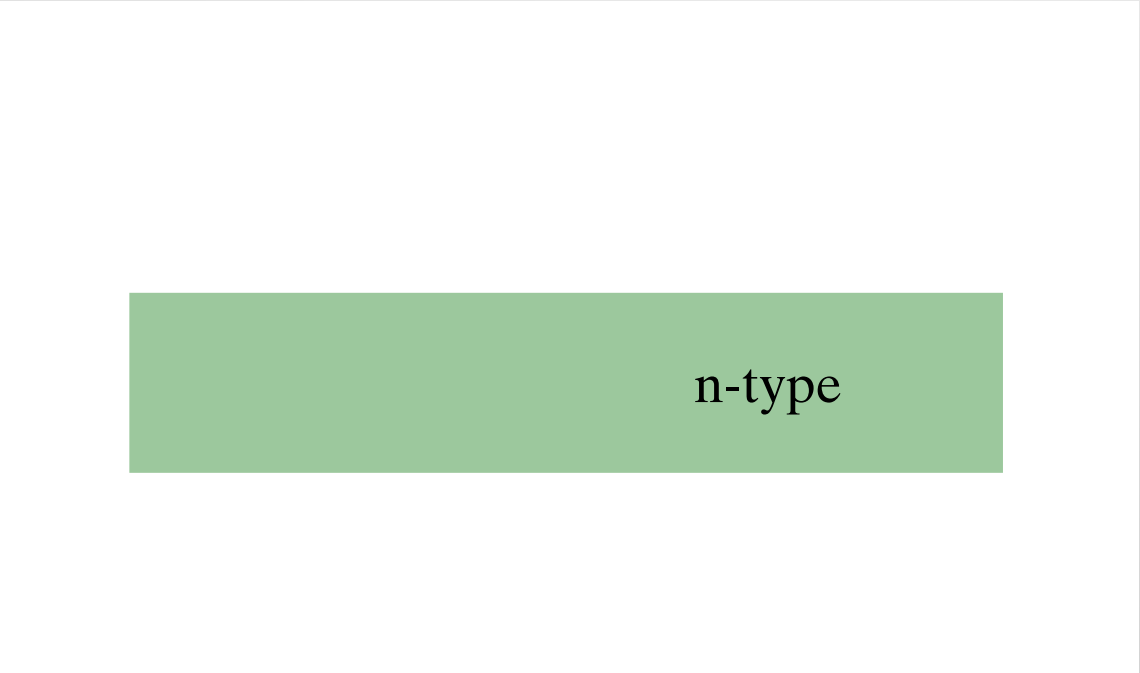


E-field separates eh-pair, causing current

pn-junctions

how to make a miniature diode on a chip?

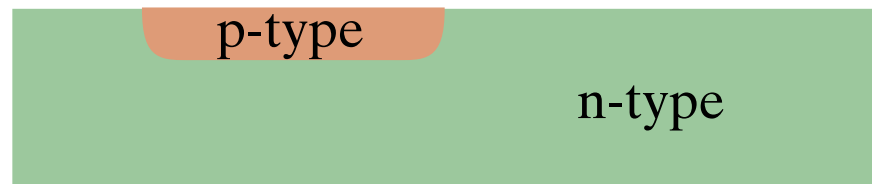
pn-junctions



n-type

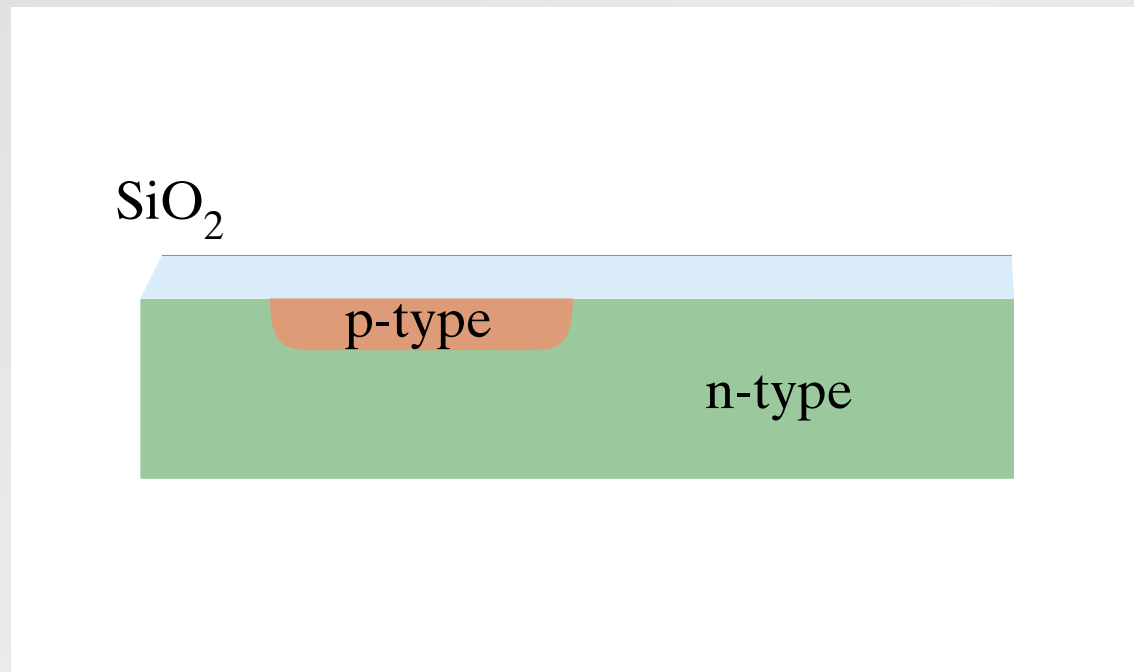
begin with an *n*-doped wafer

pn-junctions



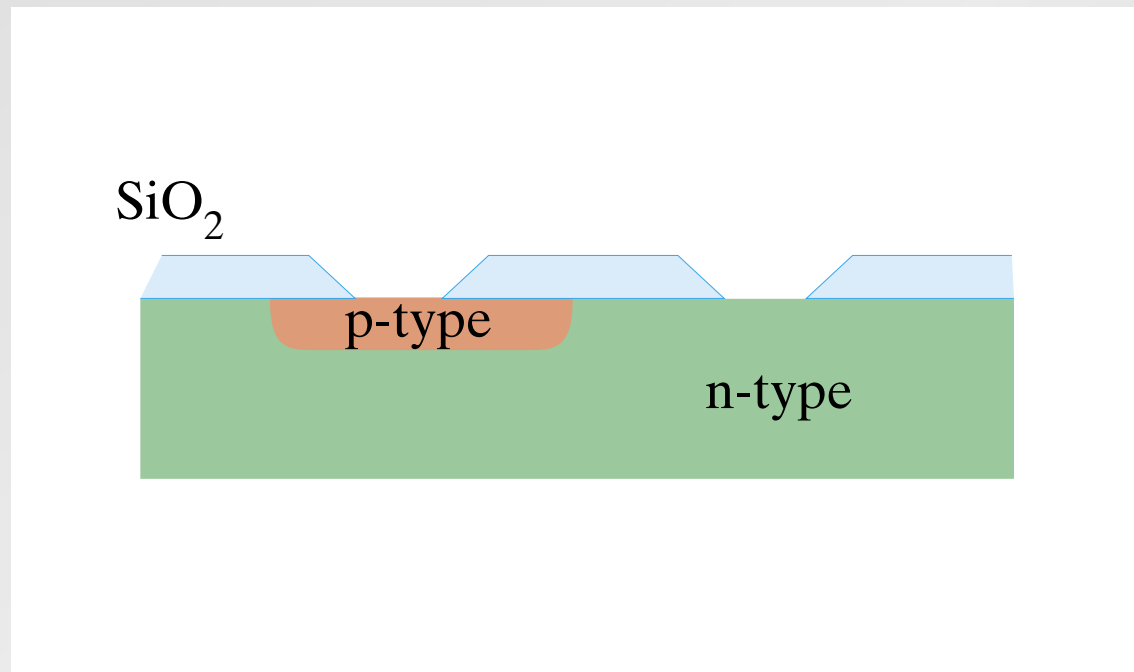
p-dope small region

pn-junctions



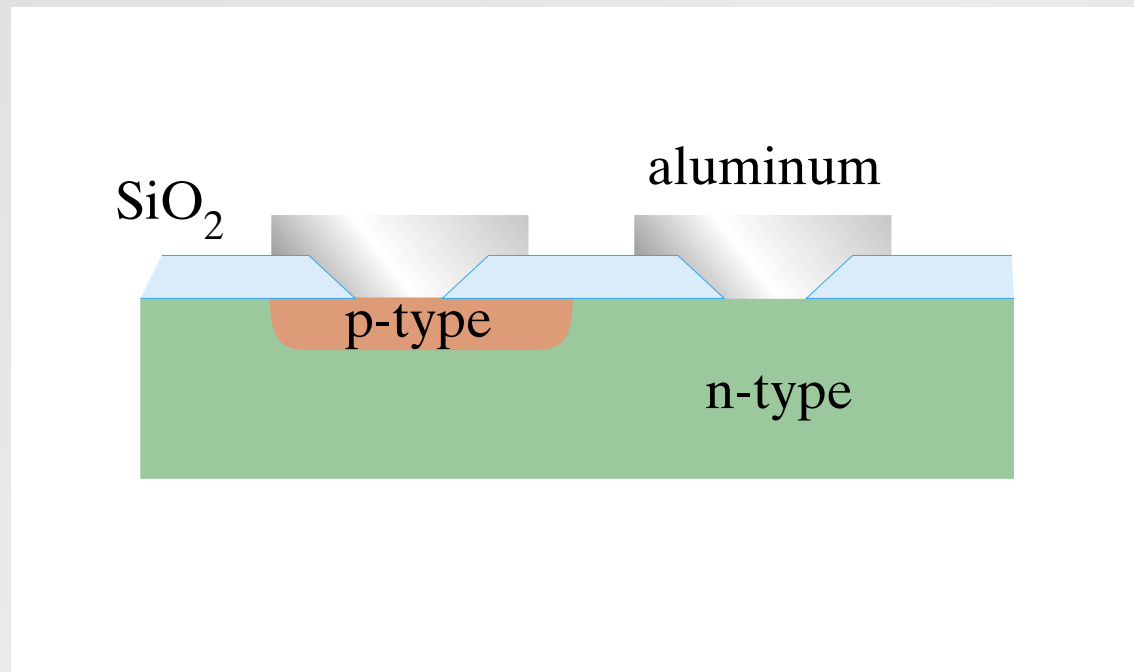
cover with insulating layer

pn-junctions



etch insulating layer

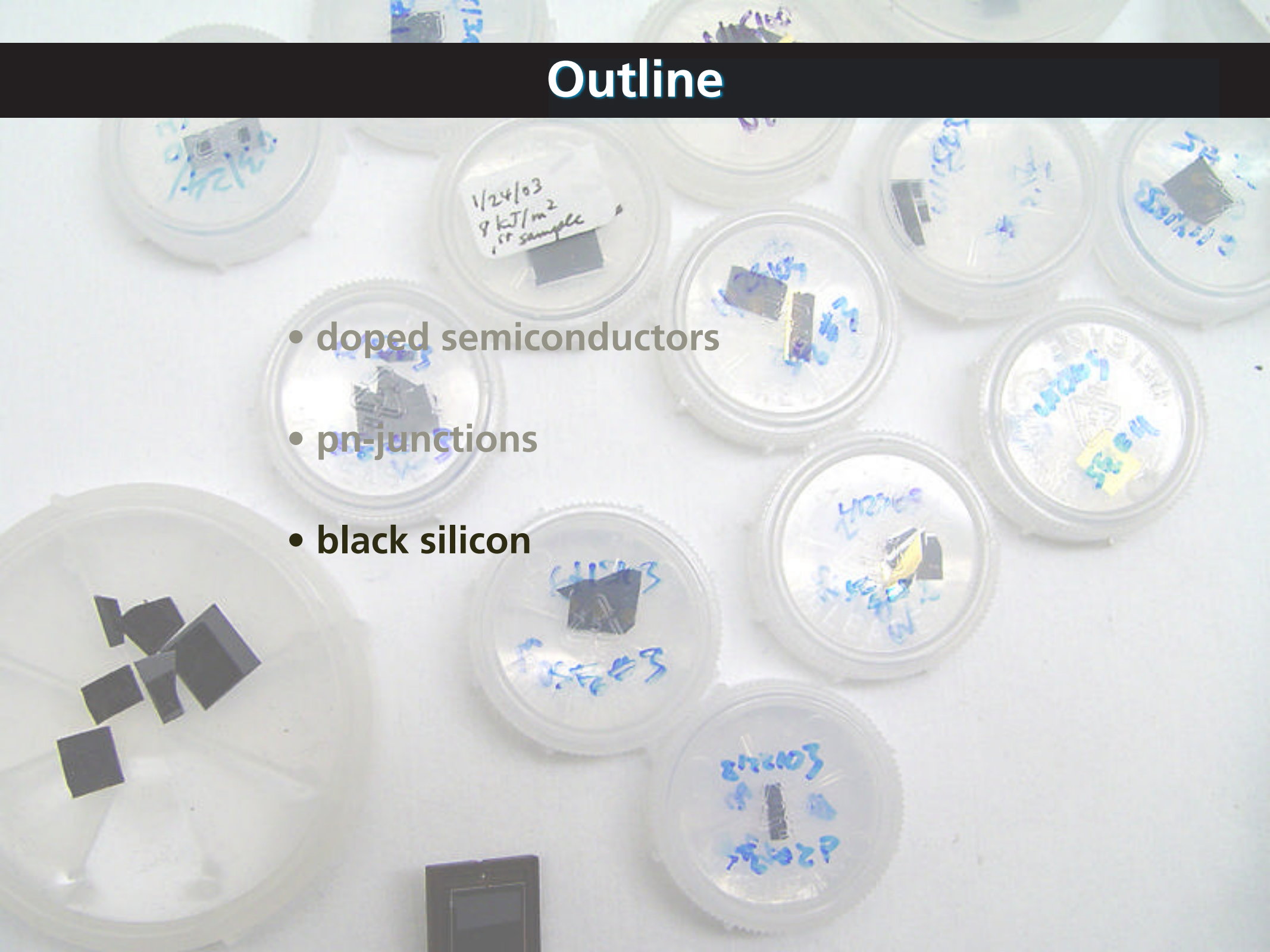
pn-junctions



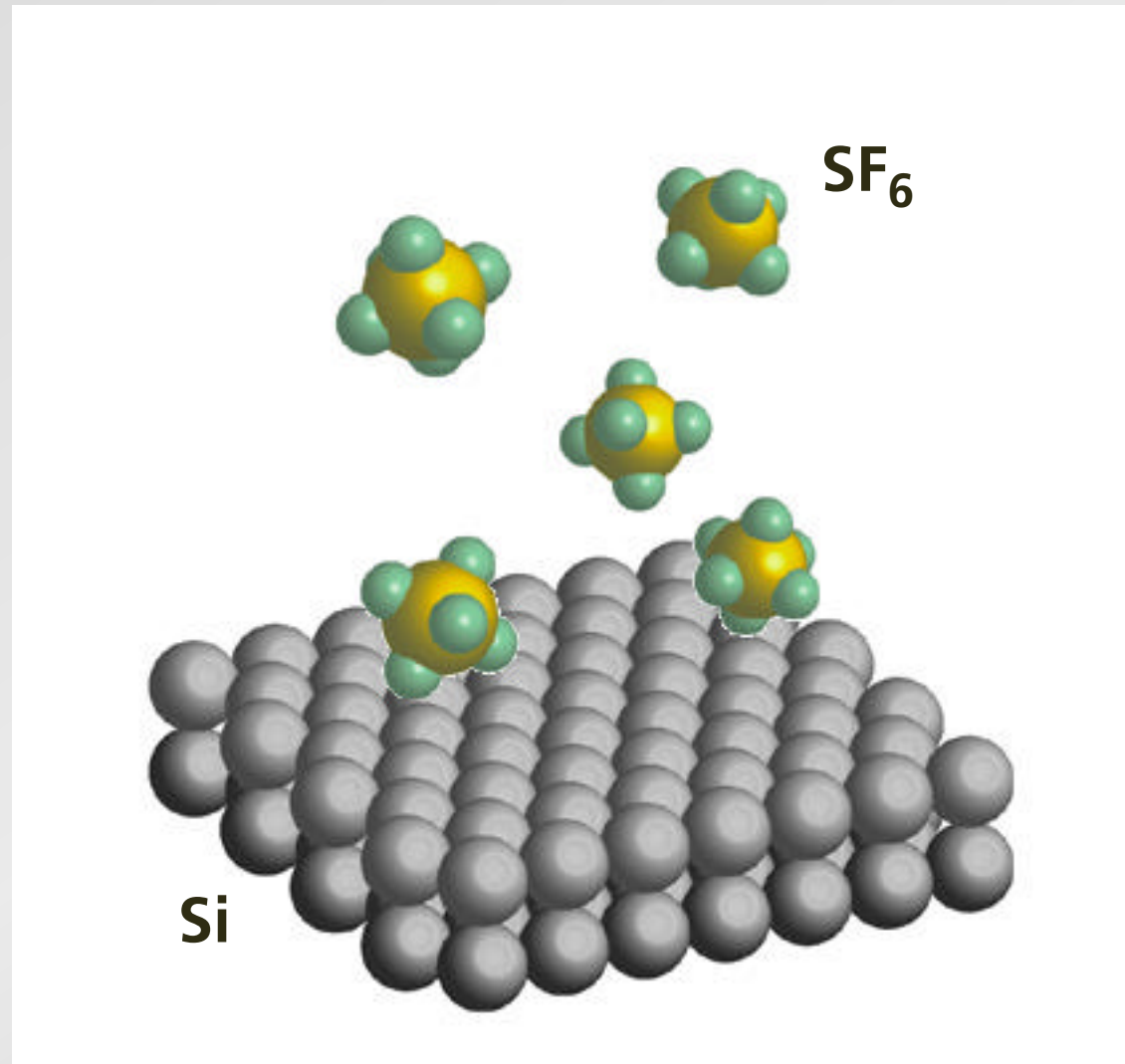
add aluminum contacts

Outline

- doped semiconductors
- pn-junctions
- black silicon

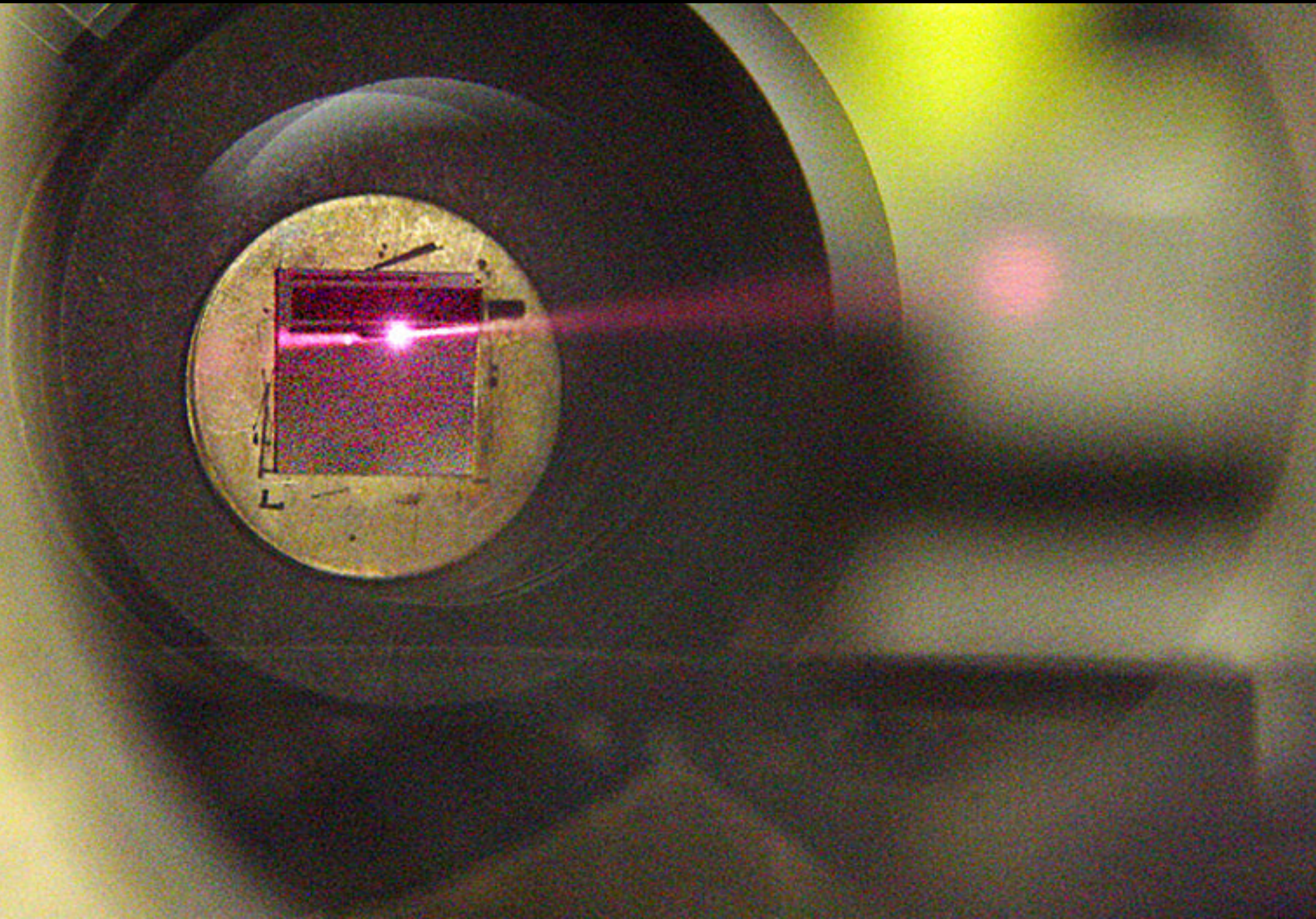


Black silicon

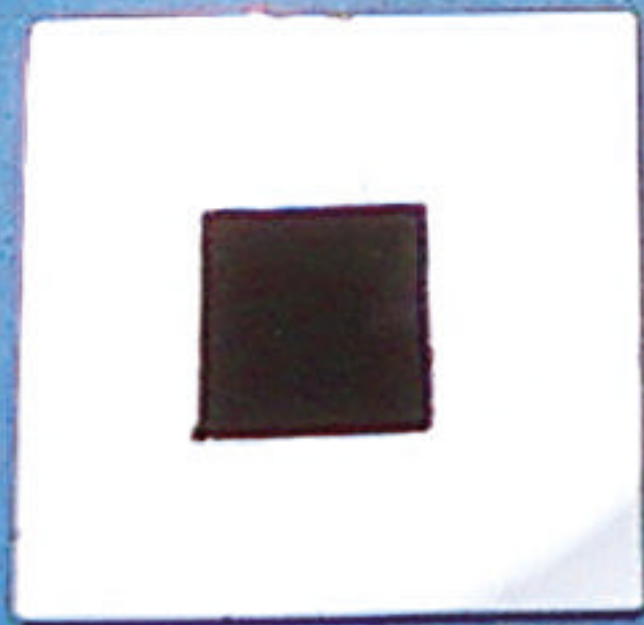


irradiate with 100-fs 10 kJ/m^2 pulses

Black silicon

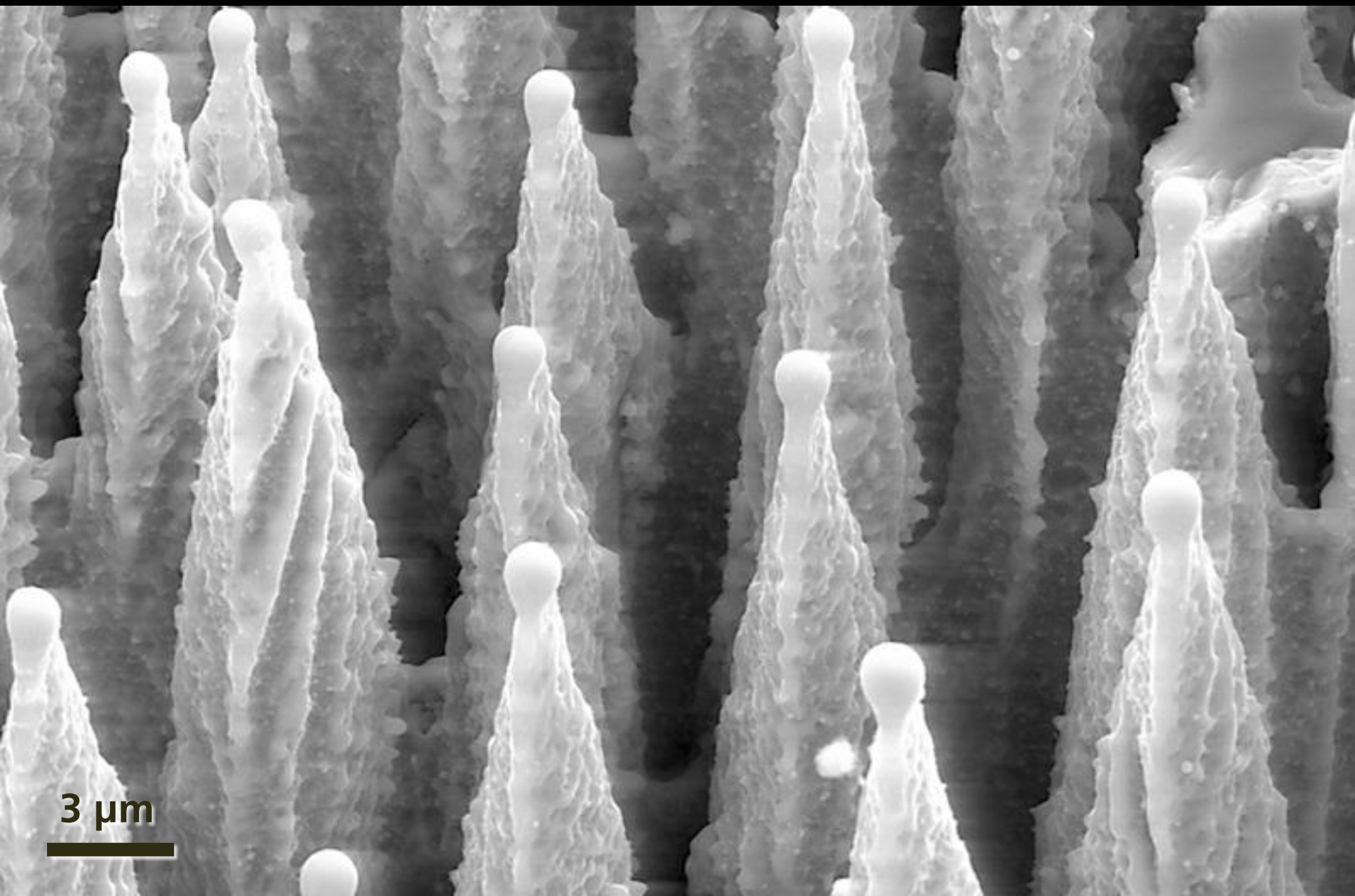


Black silicon

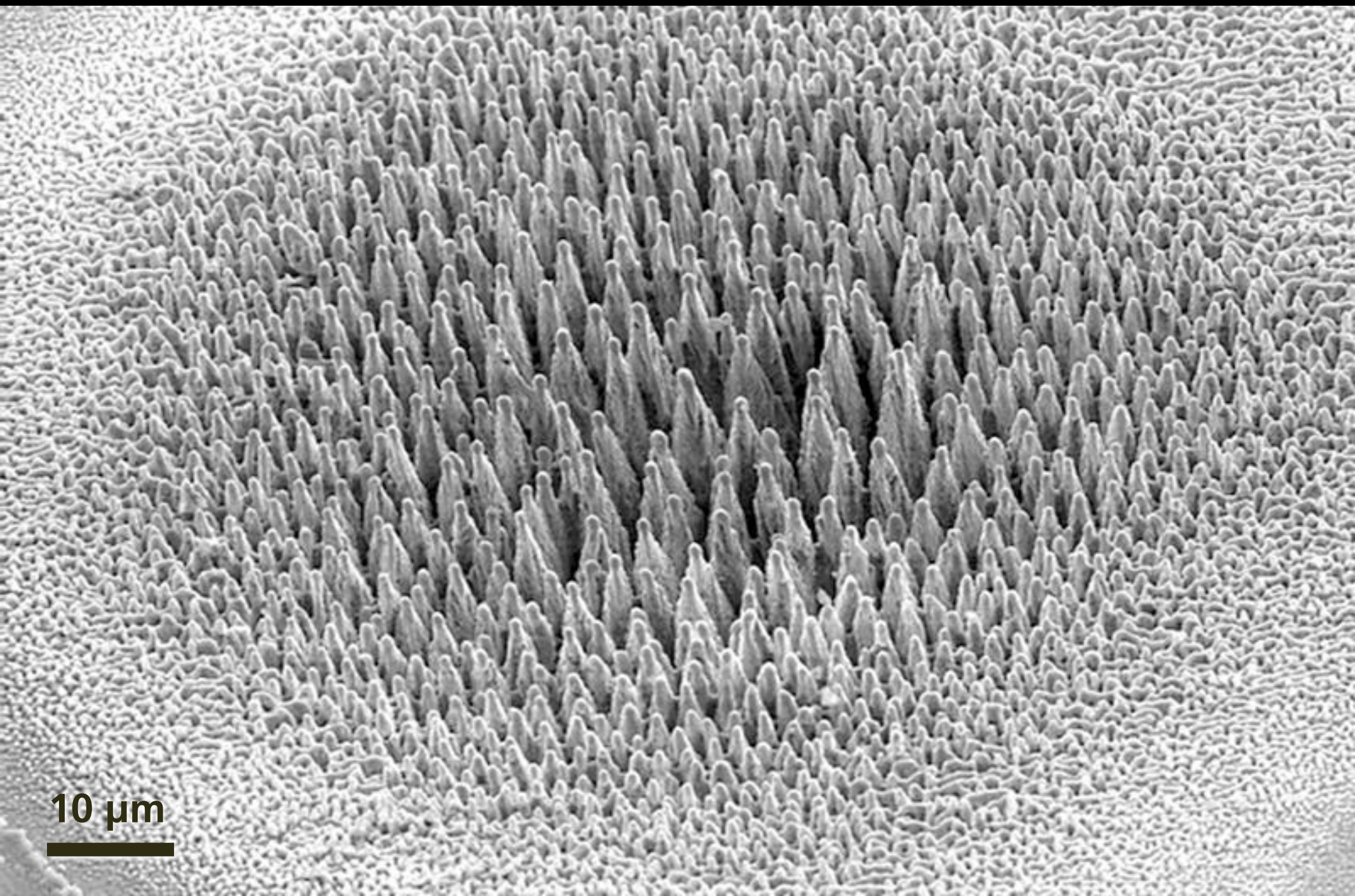


"black silicon"

Black silicon

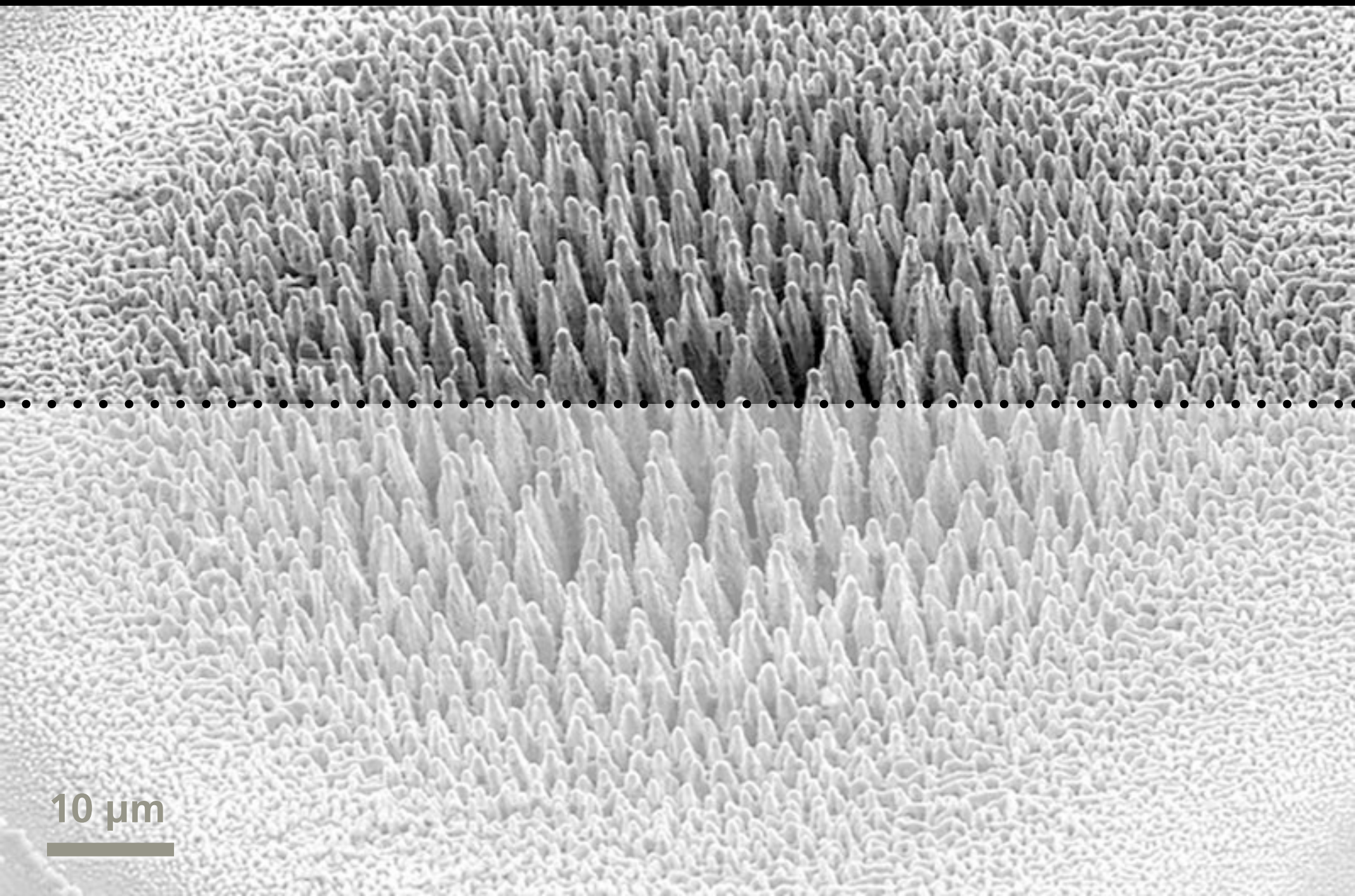


Black silicon



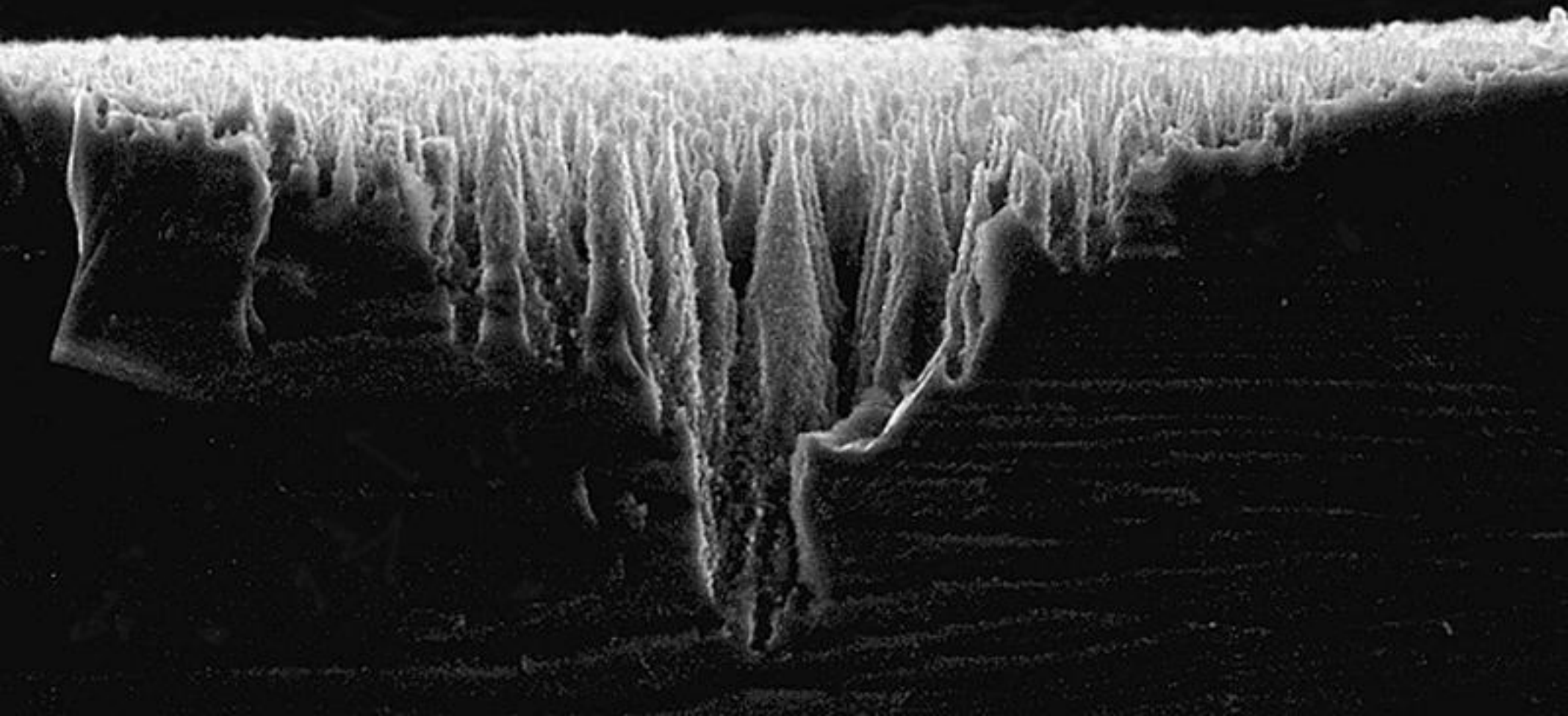
10 μm

Black silicon

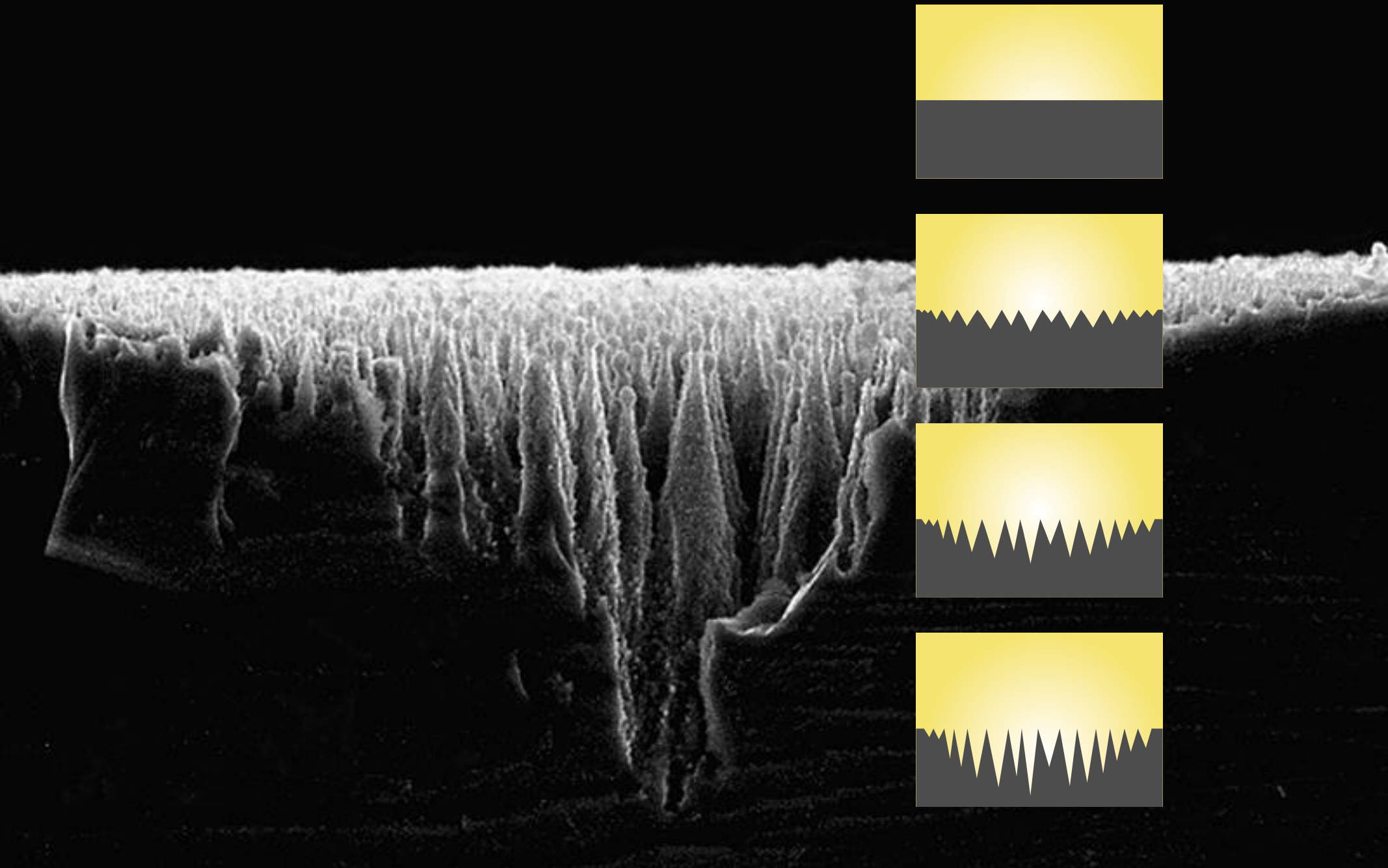


10 μm

Black silicon

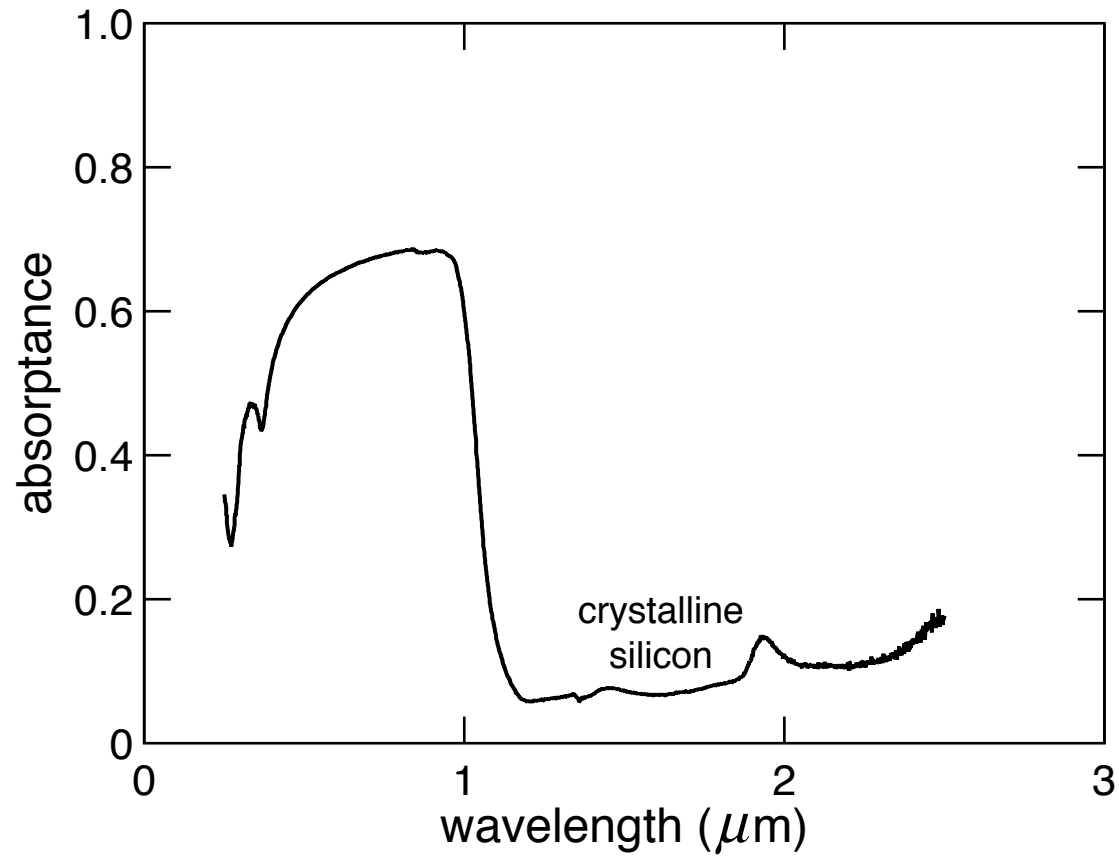


Black silicon



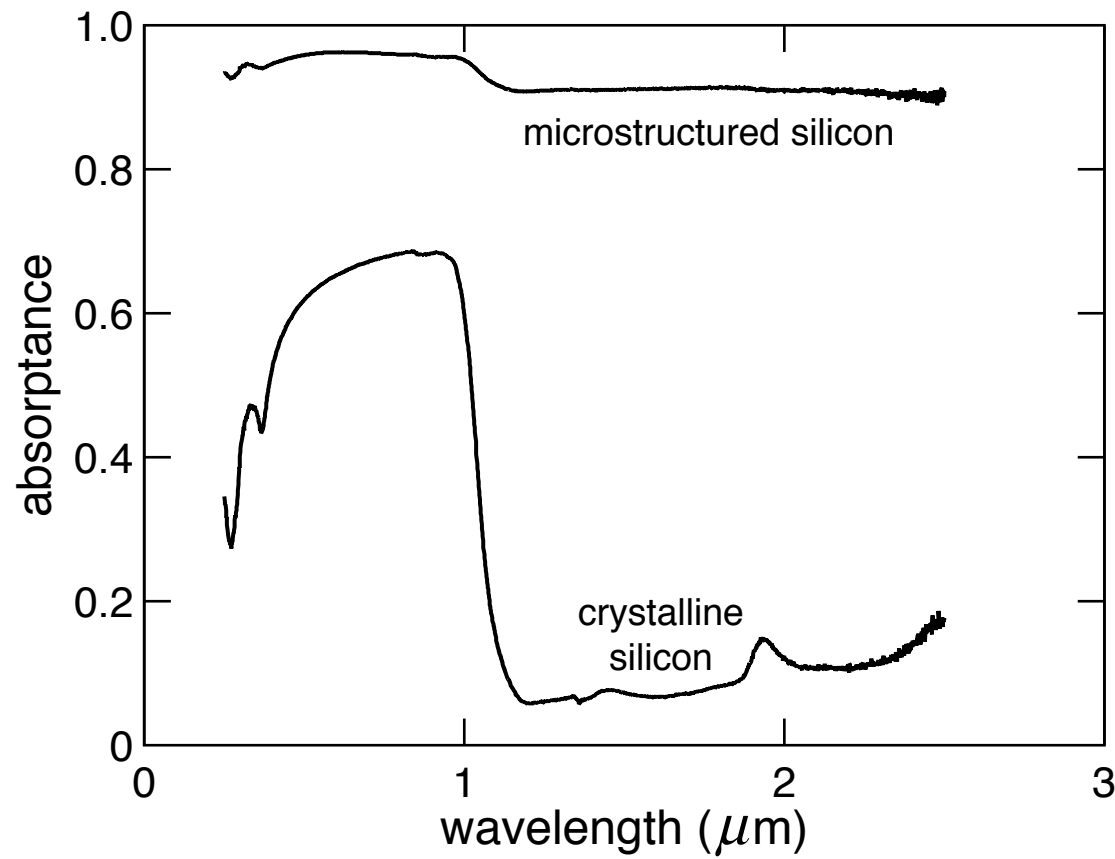
Black silicon

absorptance



Black silicon

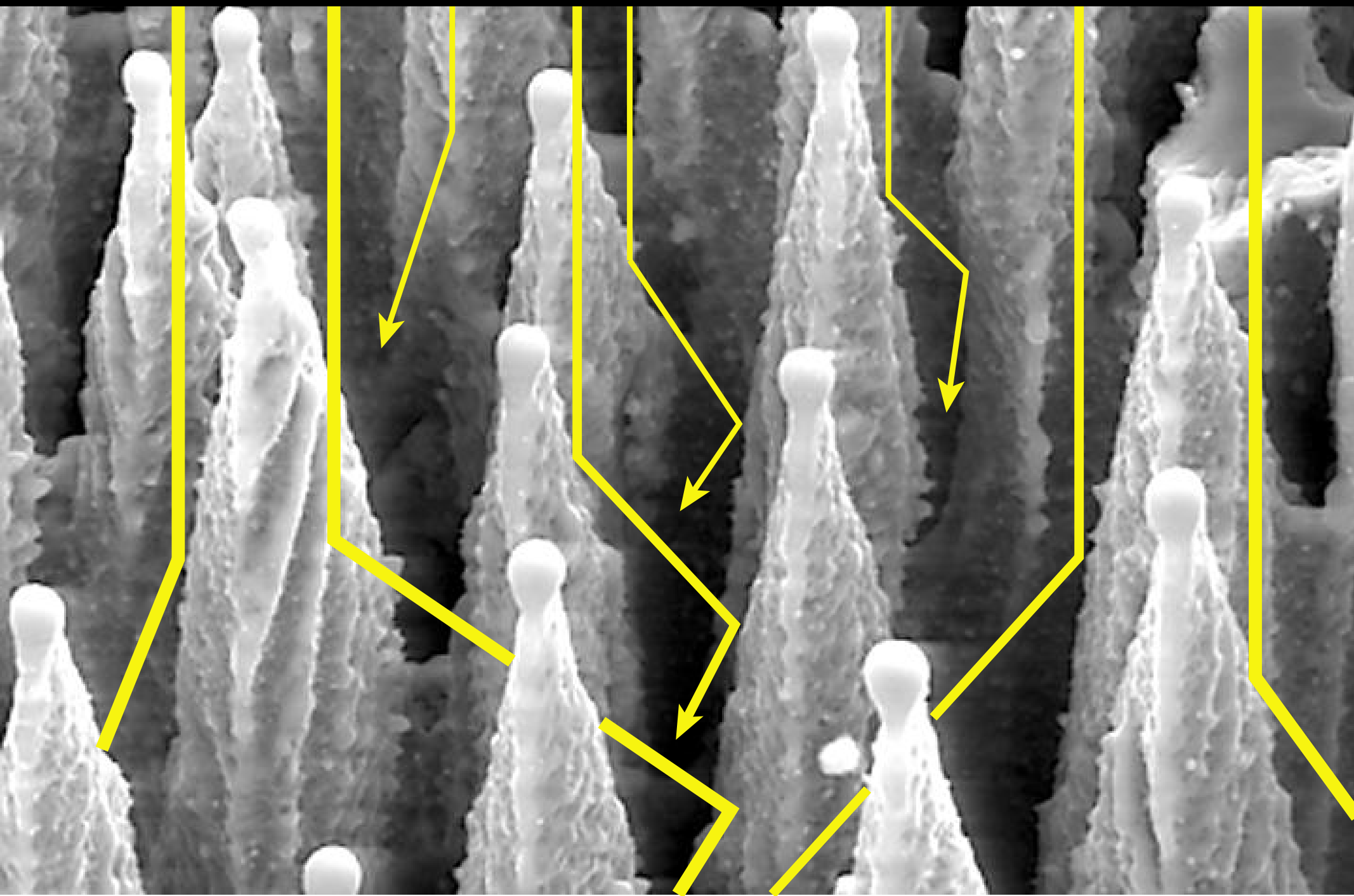
absorptance



Black silicon

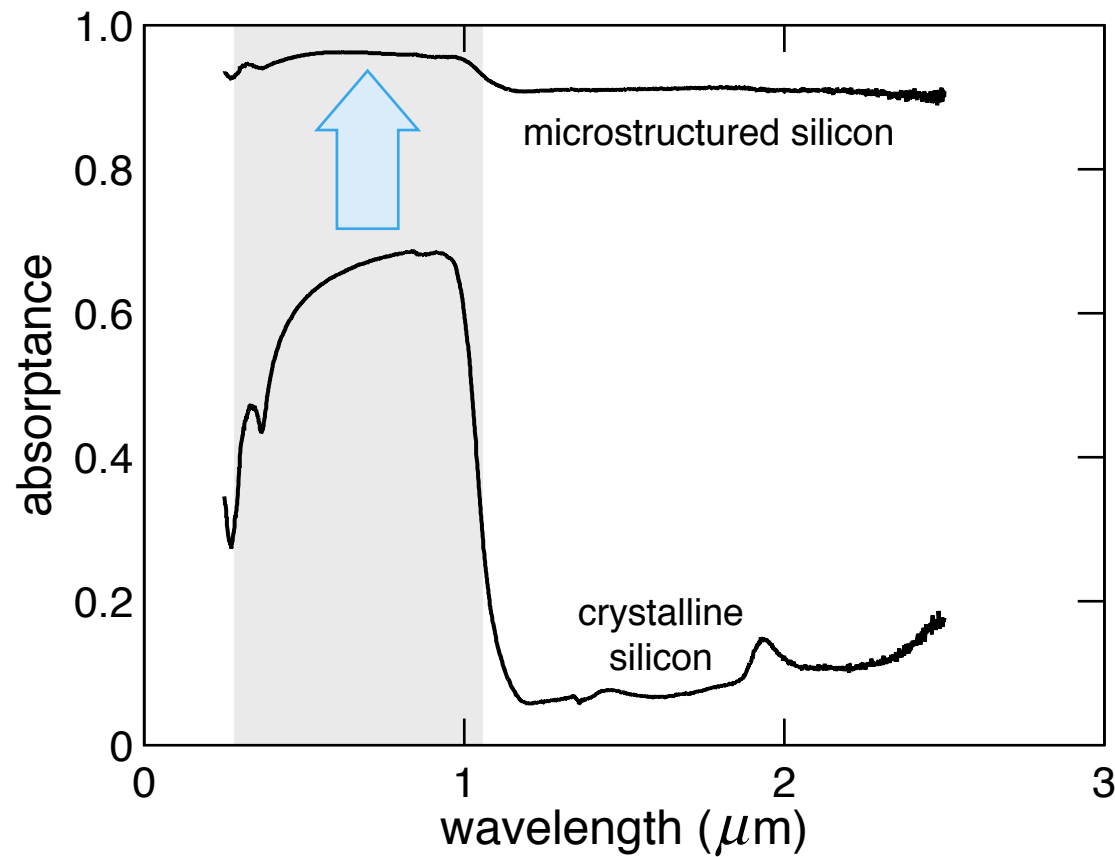
What causes the near-unity absorptance?

Black silicon



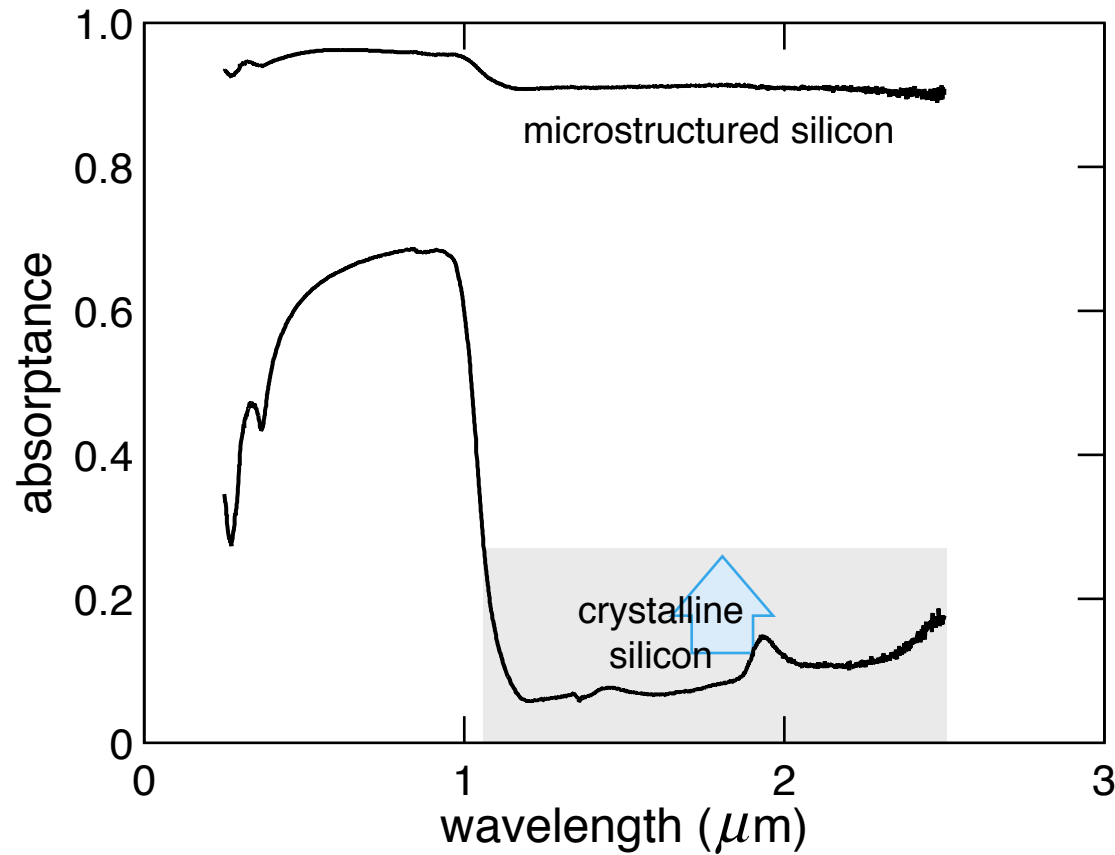
Black silicon

multiple reflections enhance absorption



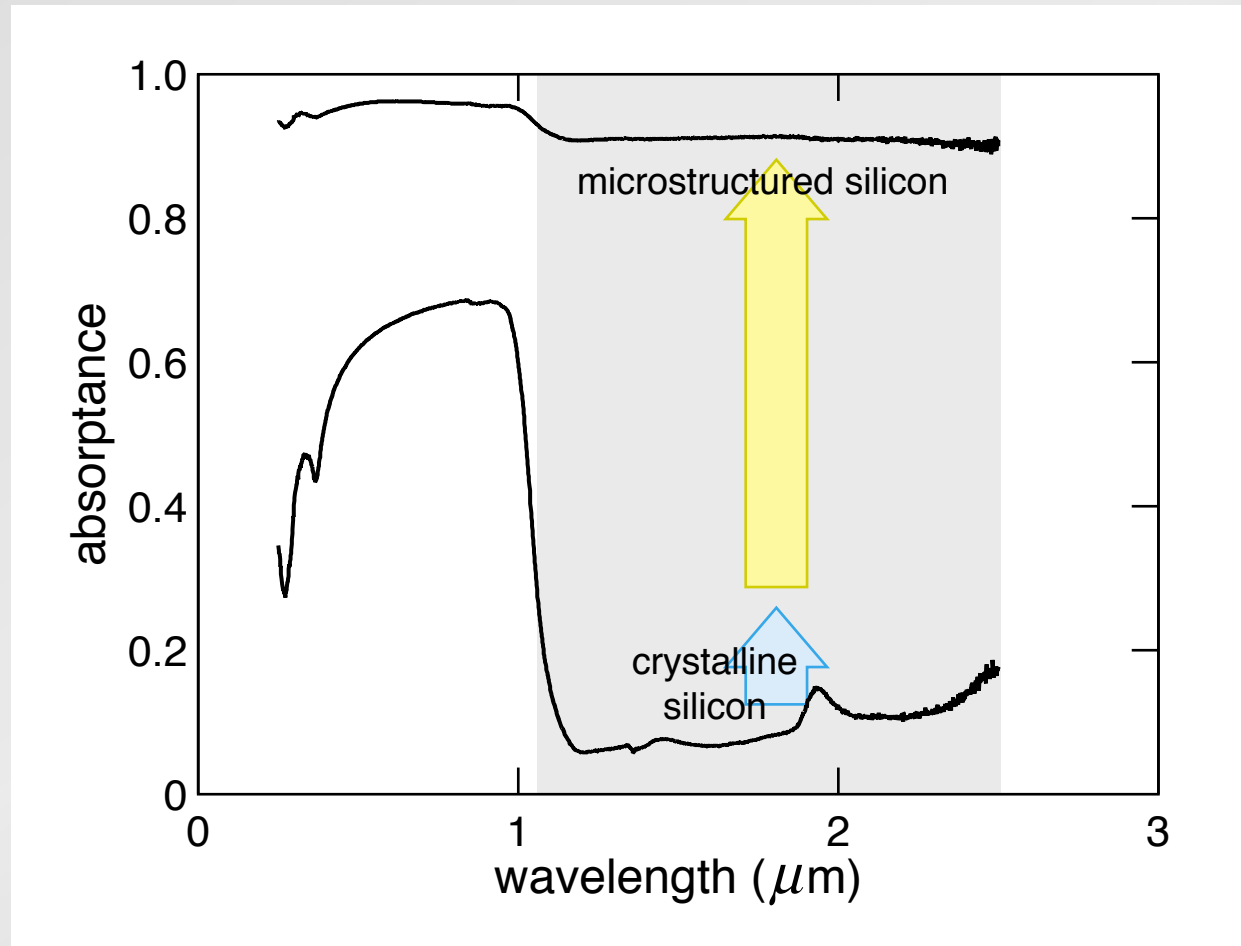
Black silicon

multiple reflections enhance absorption

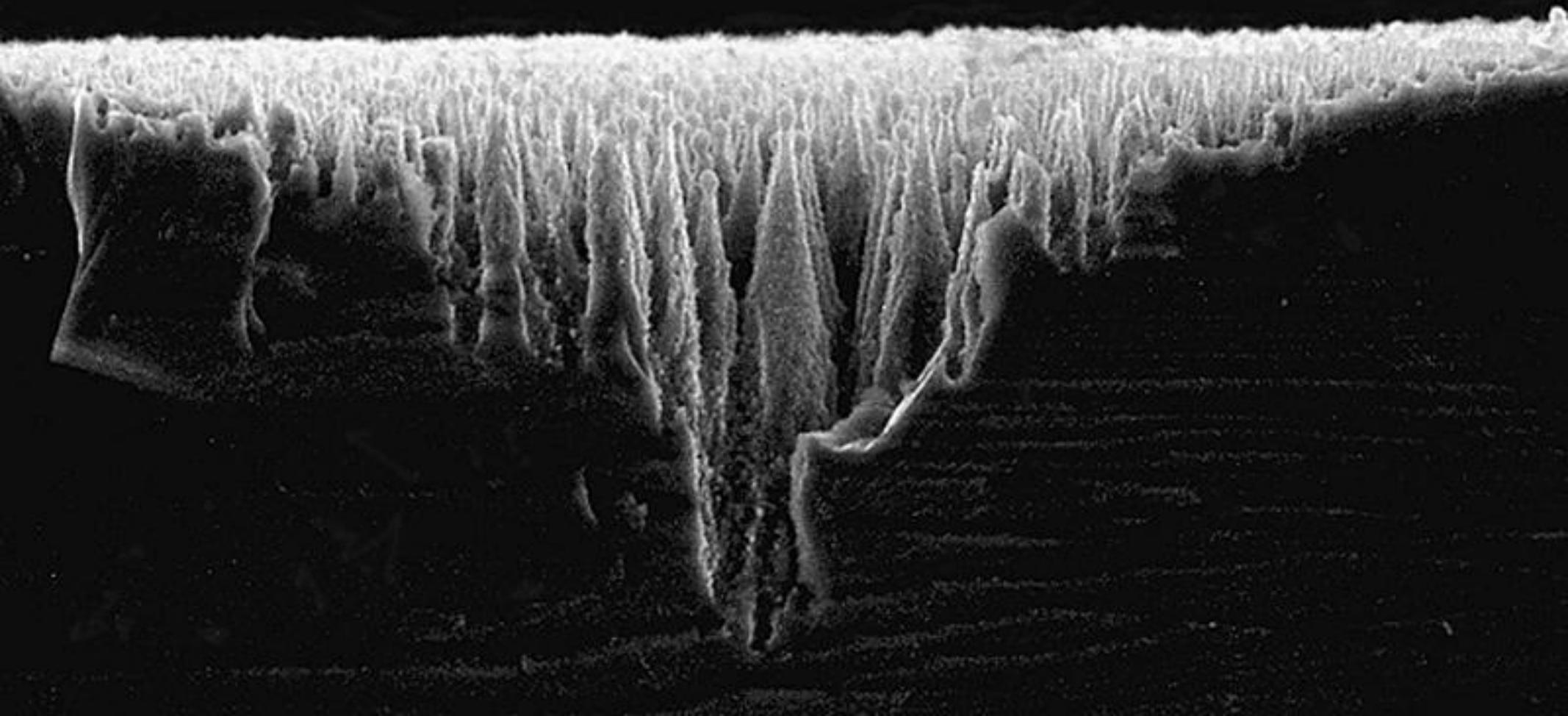


Black silicon

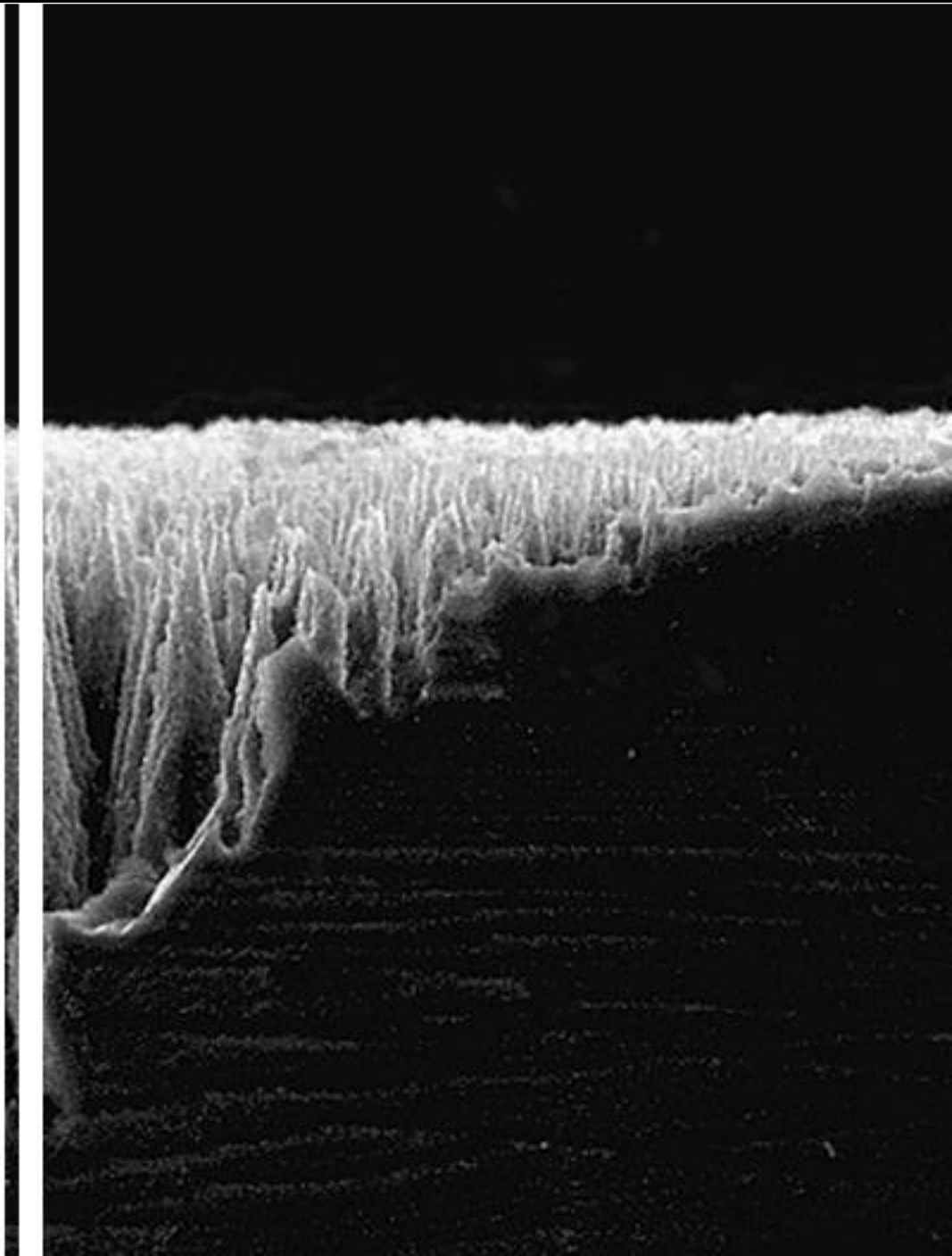
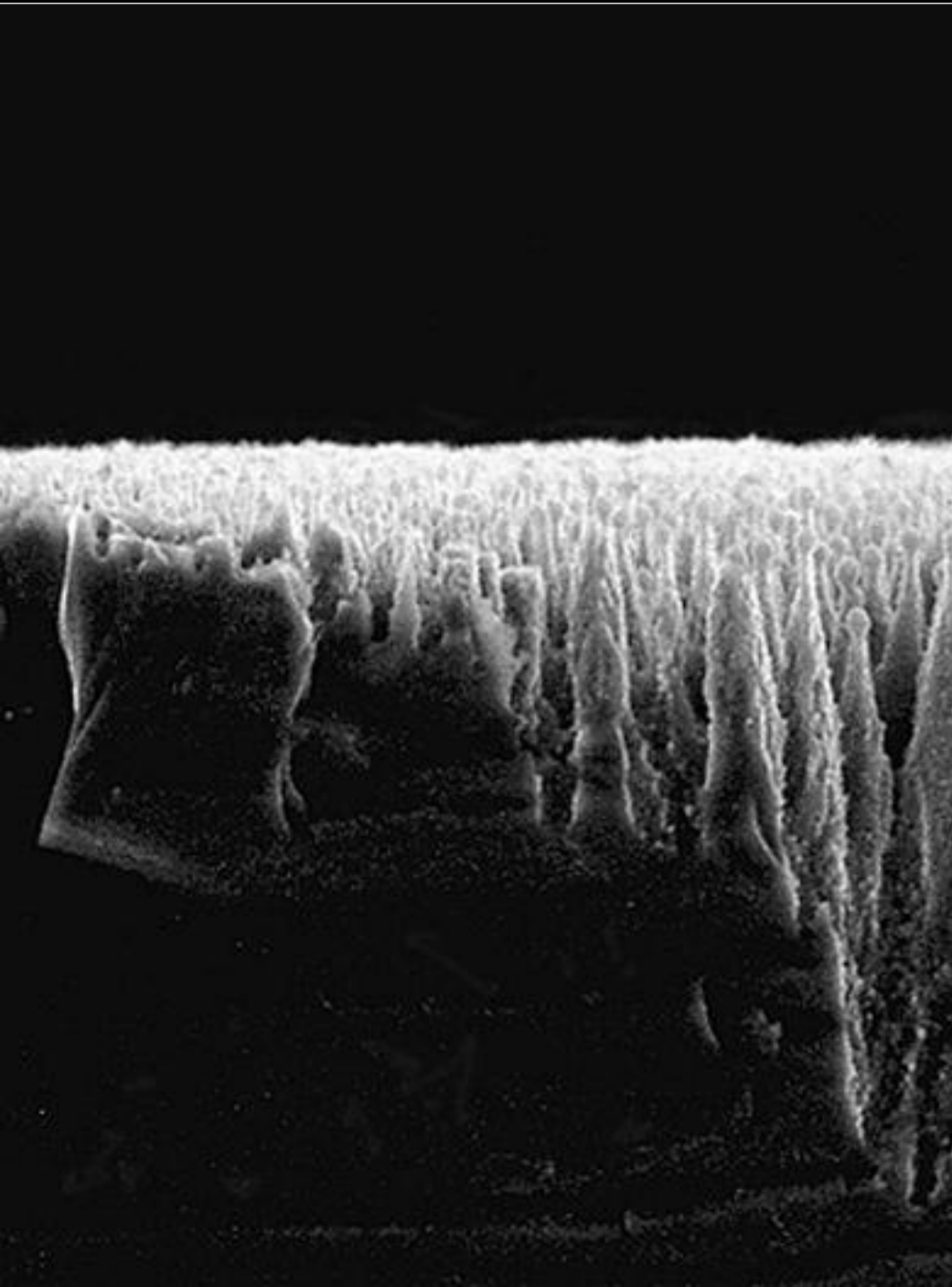
heavy sulfur doping causes infrared absorption



Black silicon

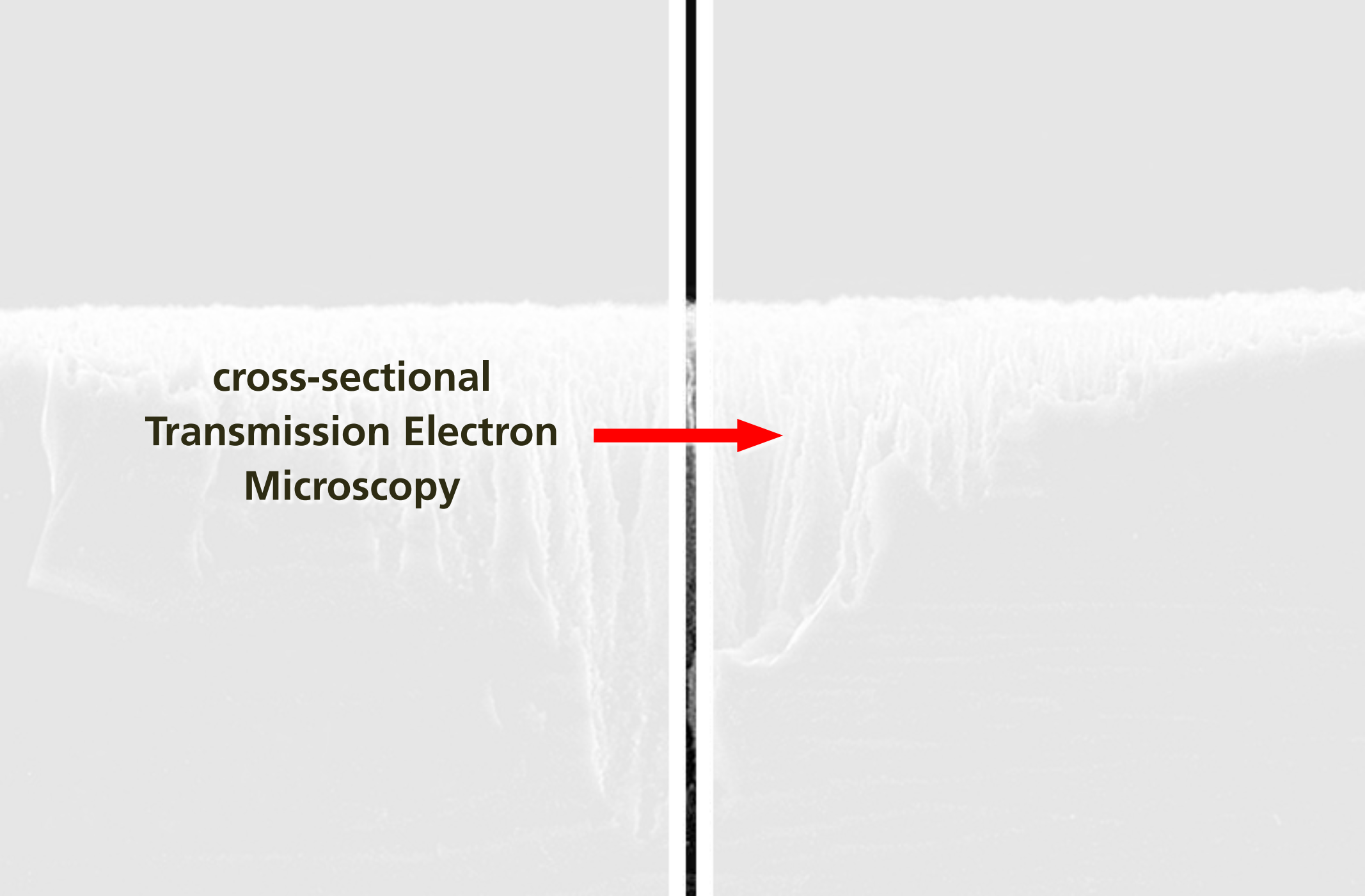


Black silicon



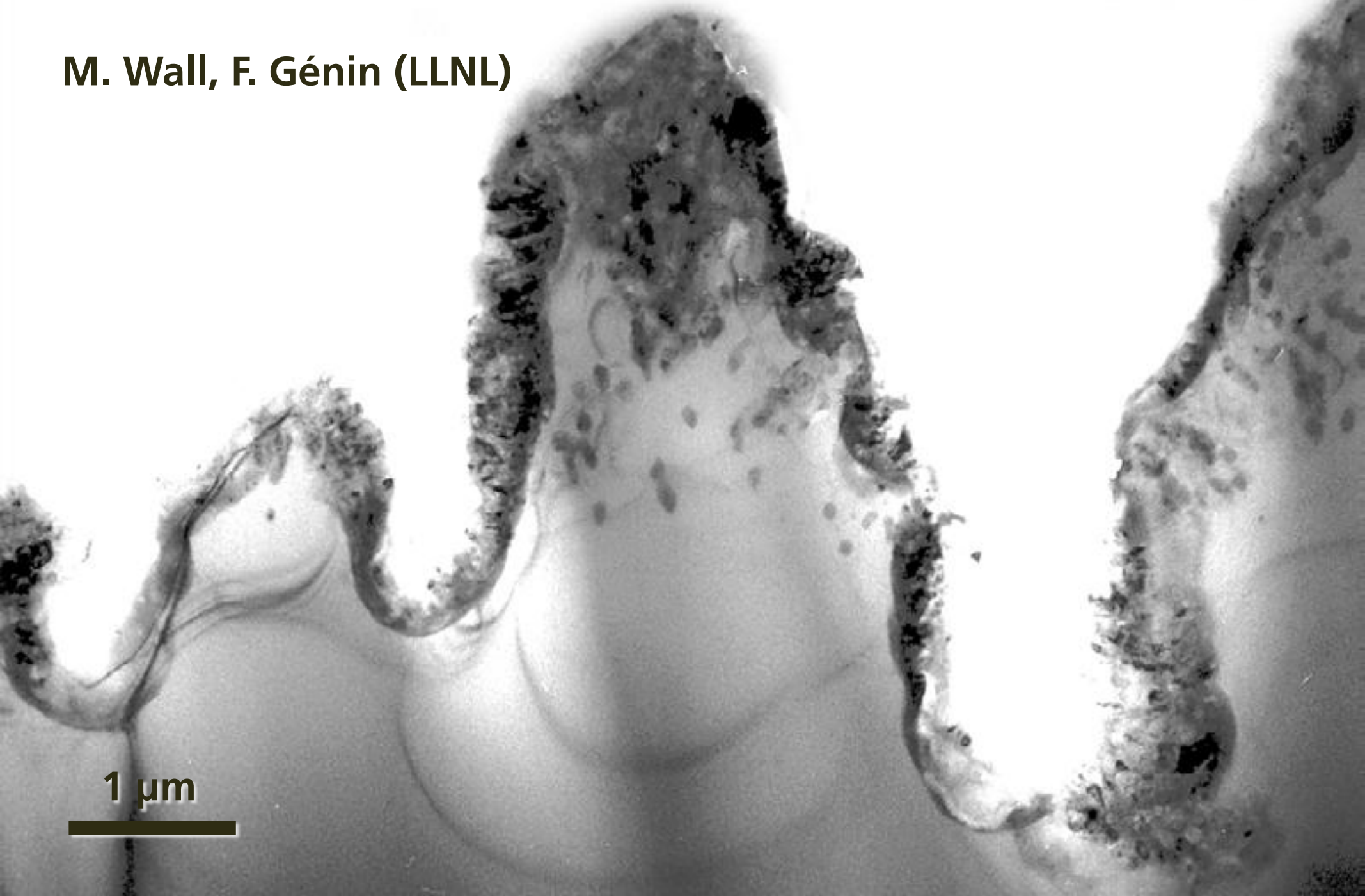
Black silicon

**cross-sectional
Transmission Electron
Microscopy**

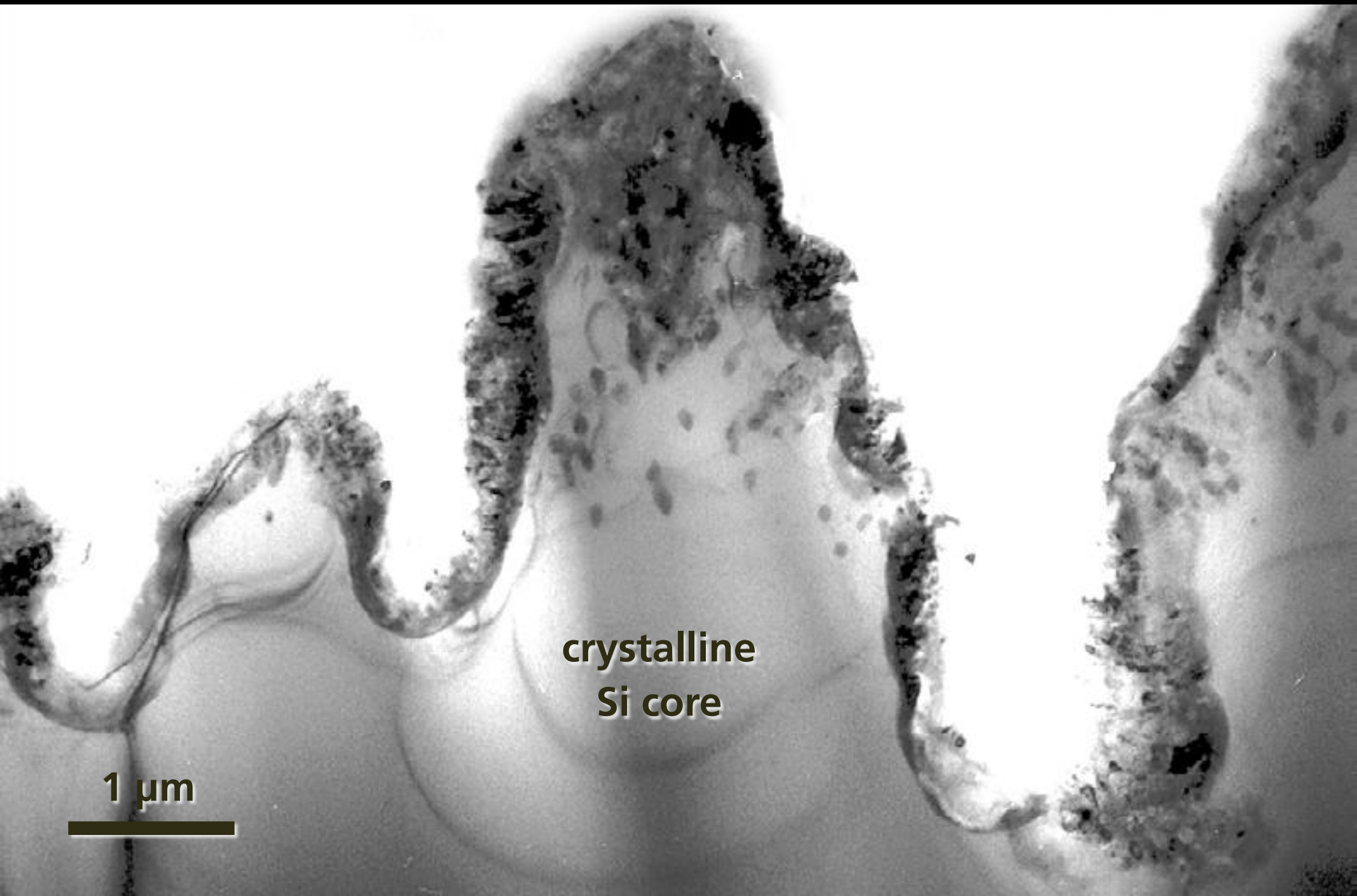


Black silicon

M. Wall, F. Génin (LLNL)



Black silicon

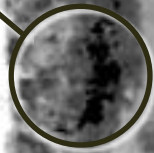


crystalline
Si core

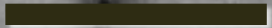
1 μm

Black silicon

sulfur-containing
surface layer

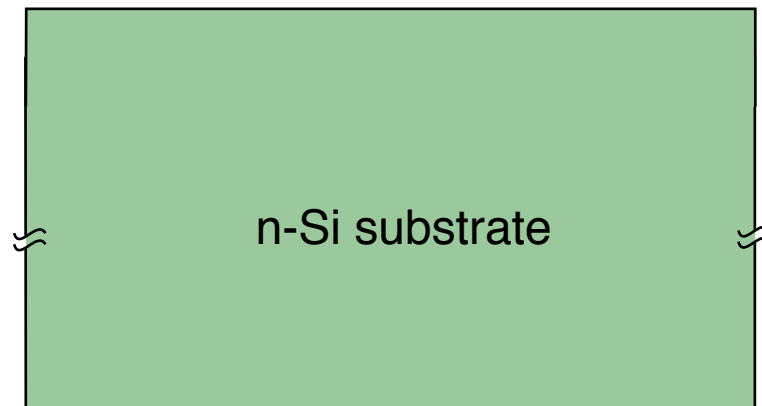


1 μm



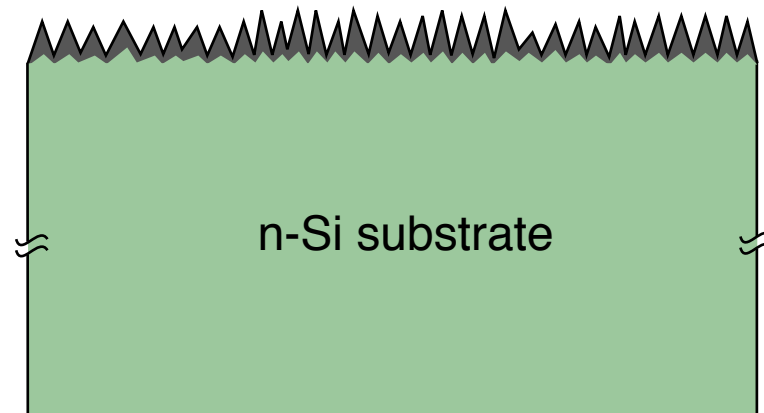
Black silicon

black silicon/n-type silicon junction



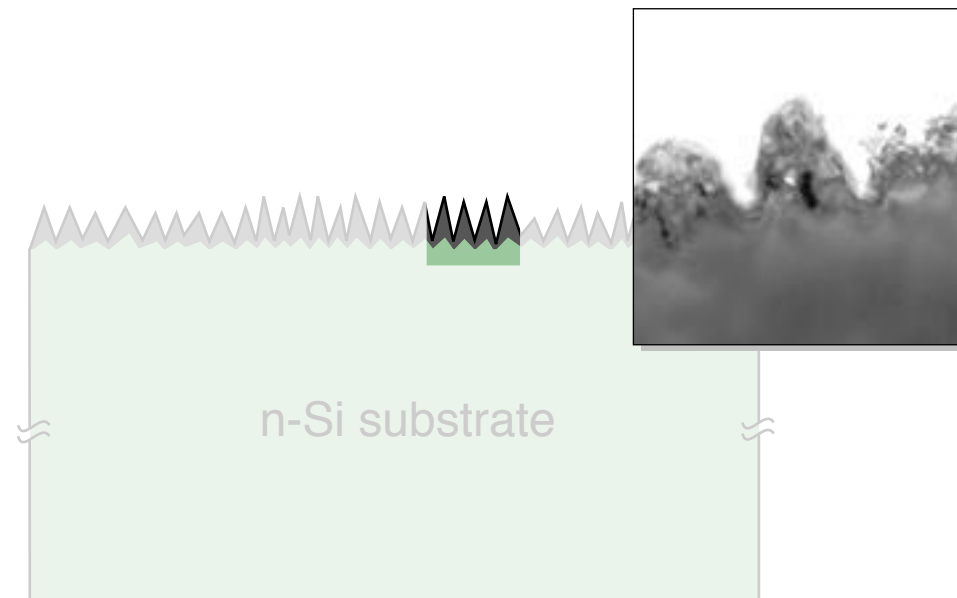
Black silicon

black silicon/n-type silicon junction



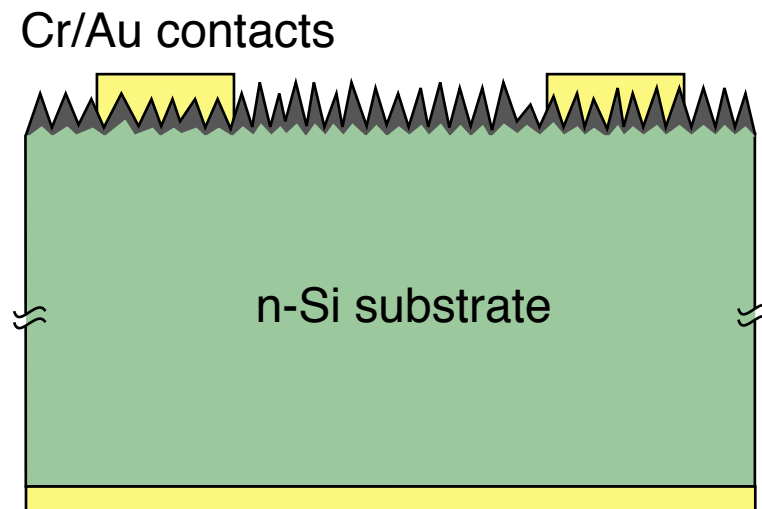
Black silicon

black silicon/n-type silicon junction



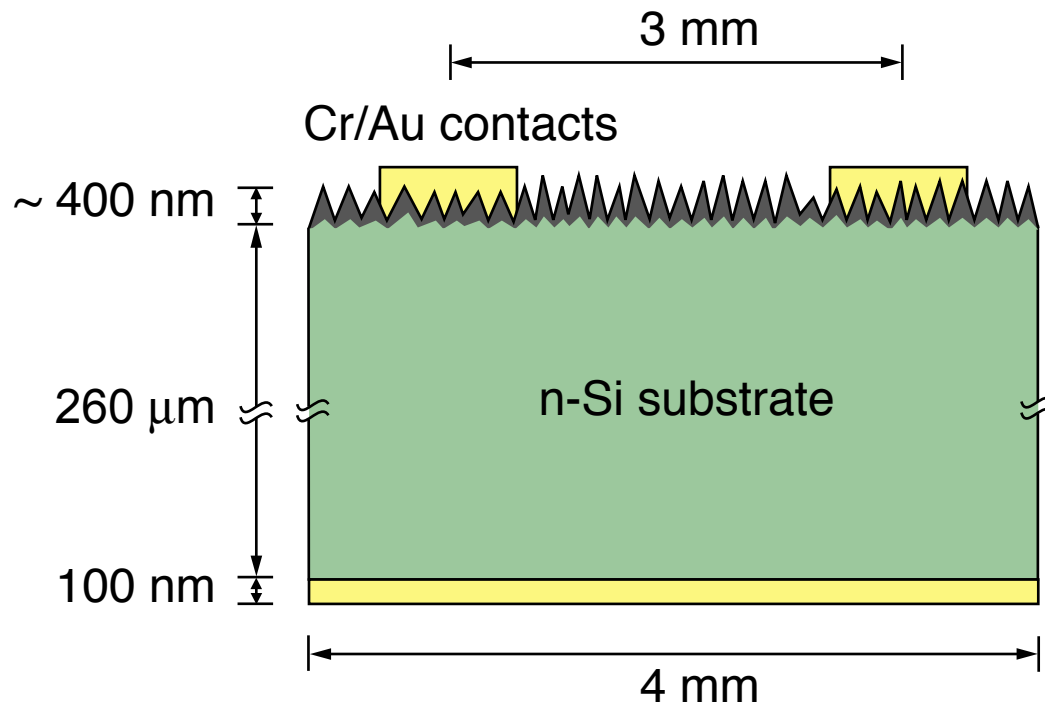
Black silicon

black silicon/n-type silicon junction



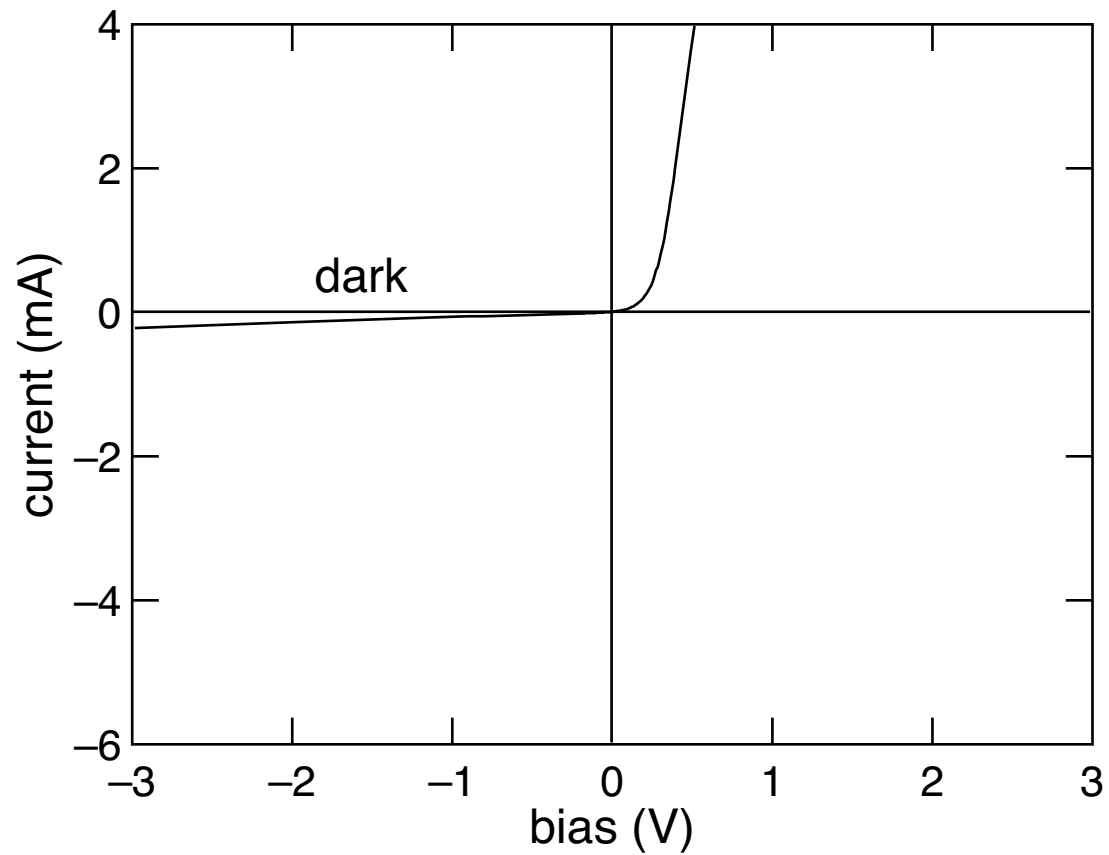
Black silicon

black silicon/n-type silicon junction



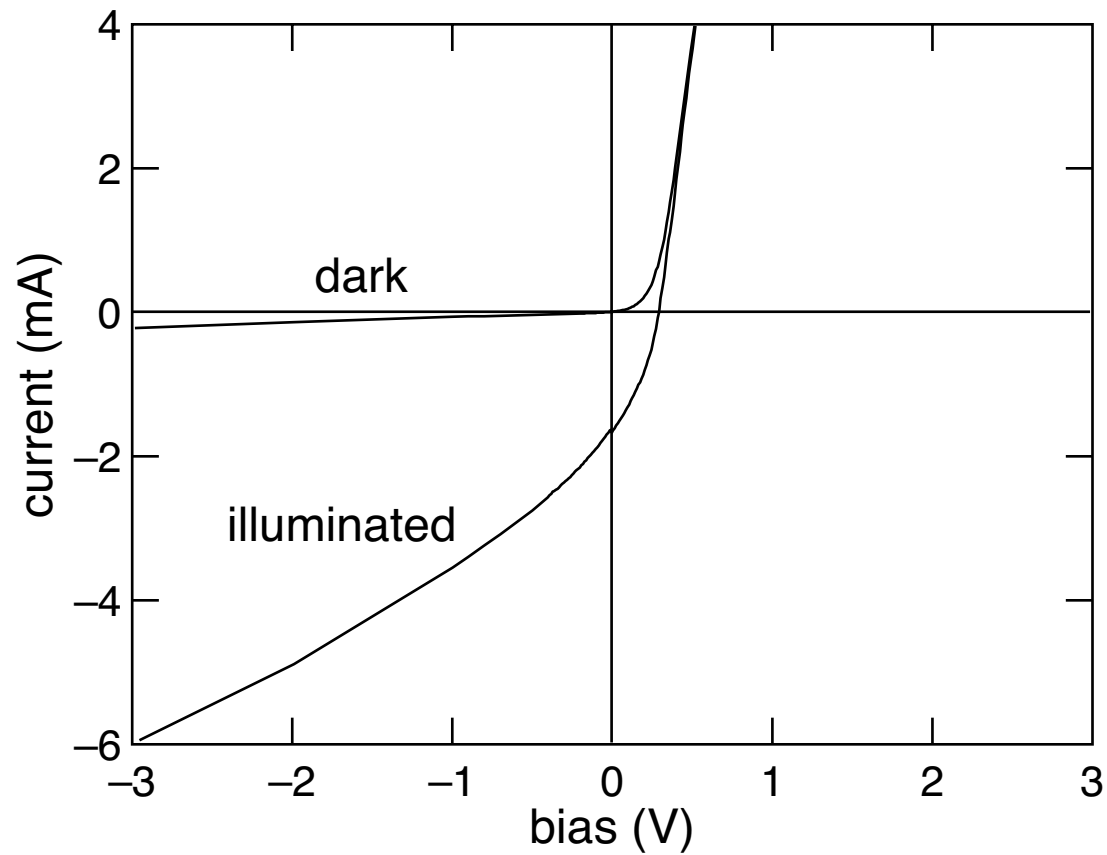
Black silicon

I/*V* characteristics



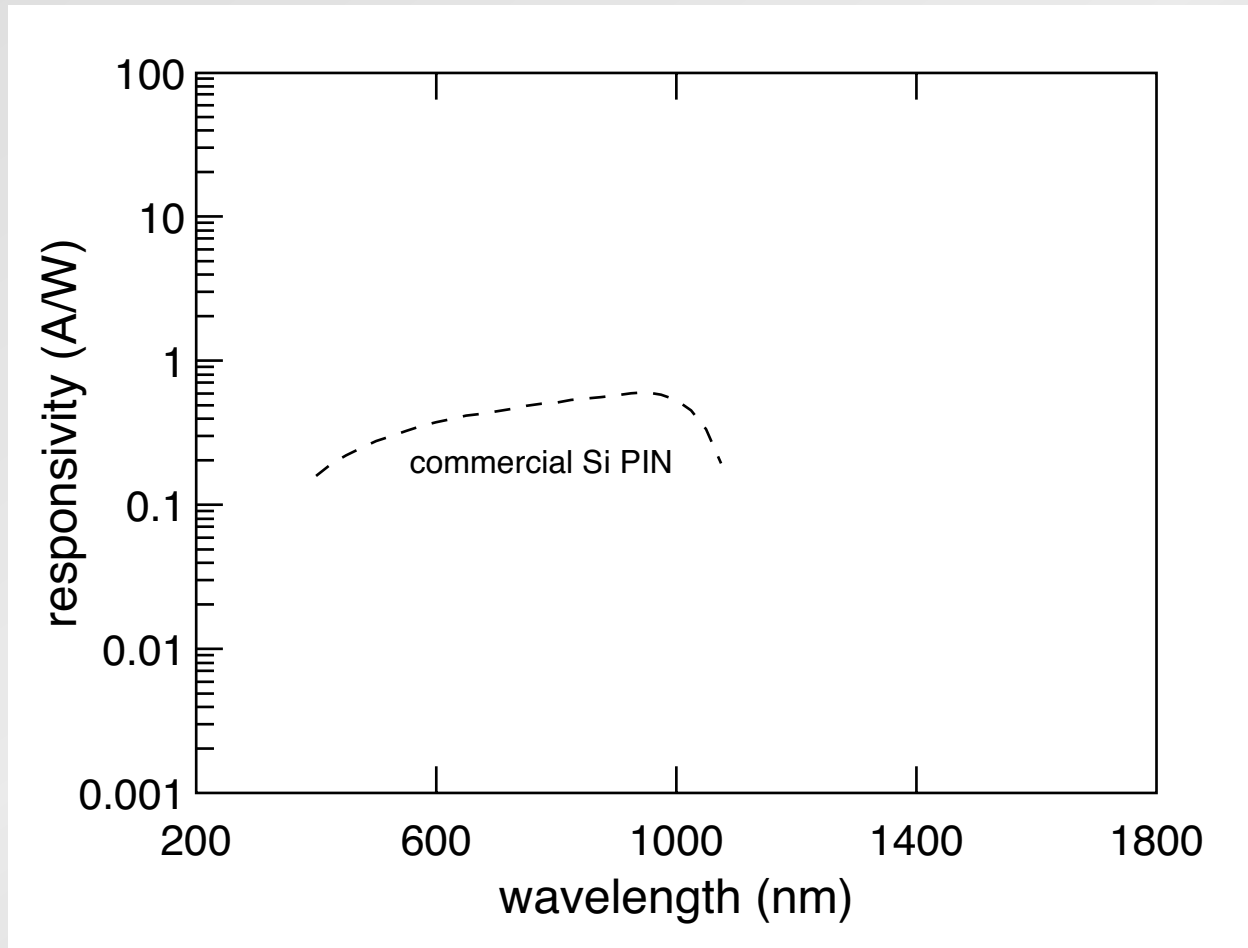
Black silicon

I/*V* characteristics



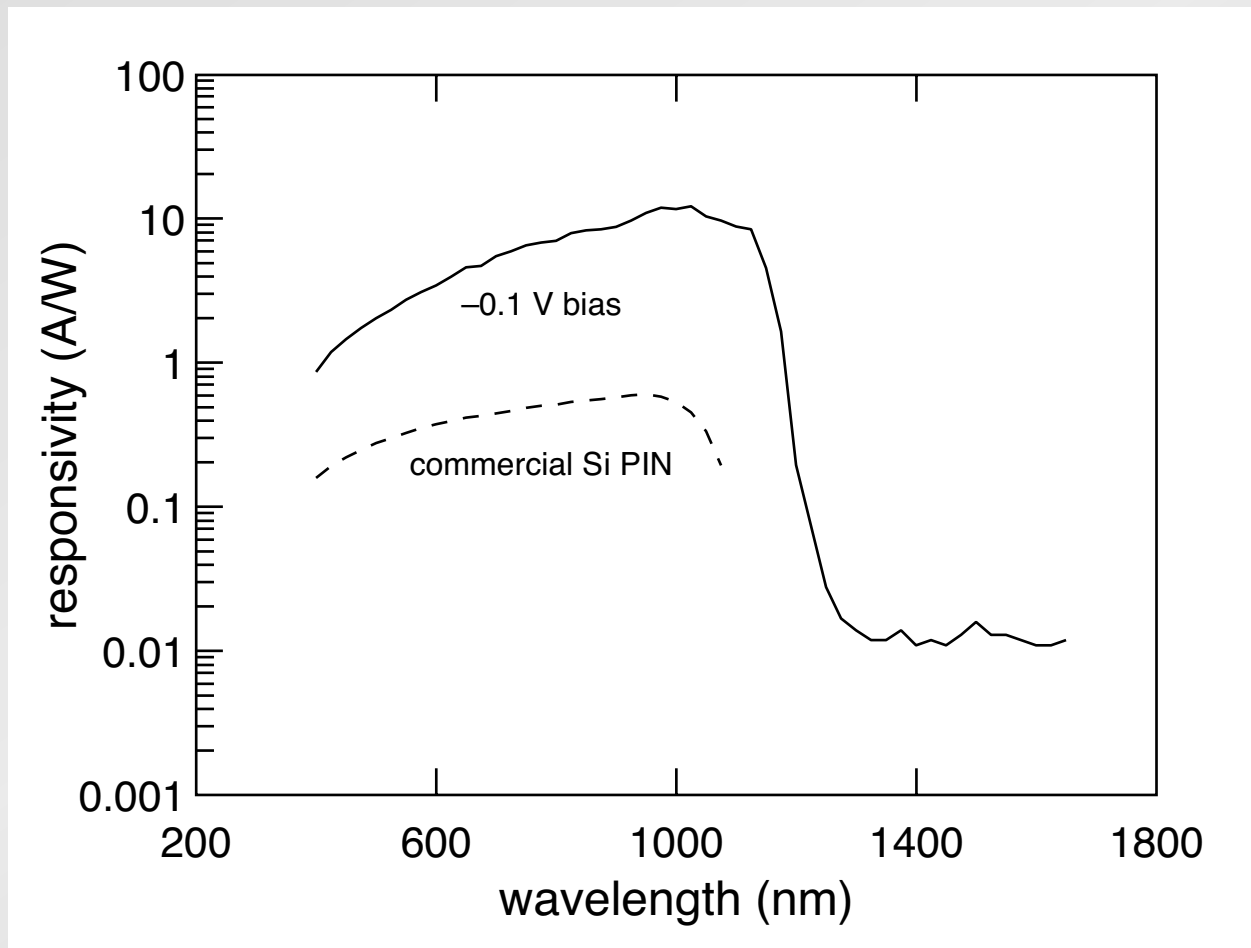
Black silicon

responsivity



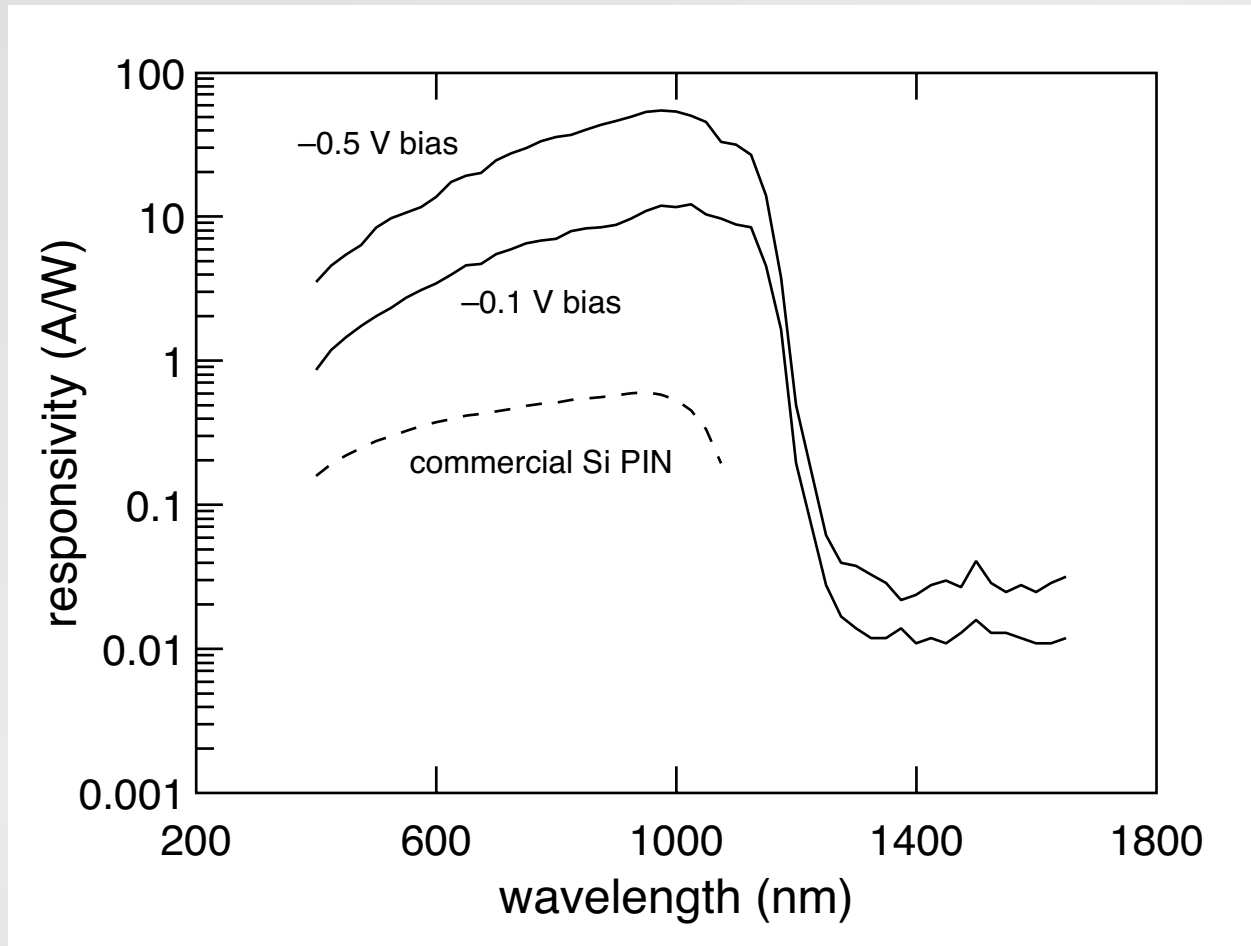
Black silicon

responsivity

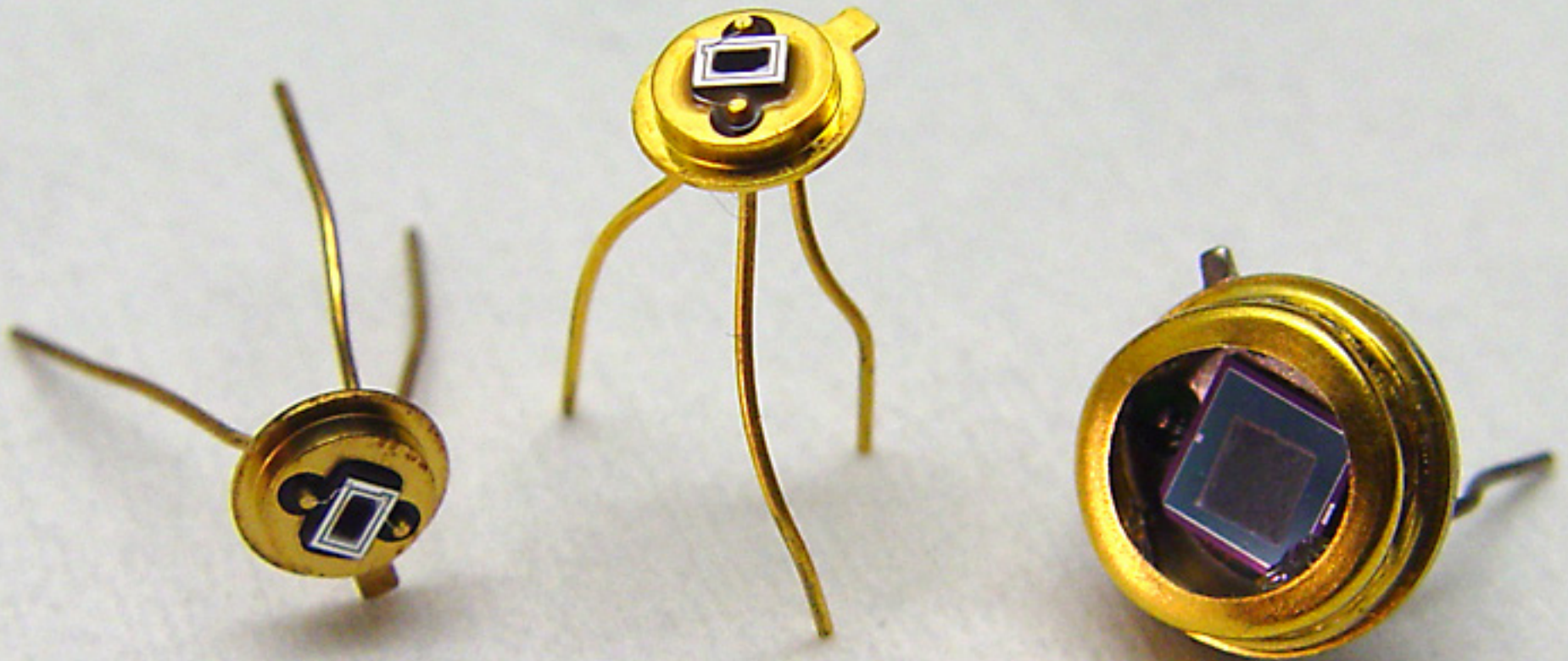


Black silicon

responsivity



Devices



Devices



SiOnyx

<http://www.sionyx.com>



Funding:

Army Research Office

DARPA

Department of Energy

NDSEG

National Science Foundation

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