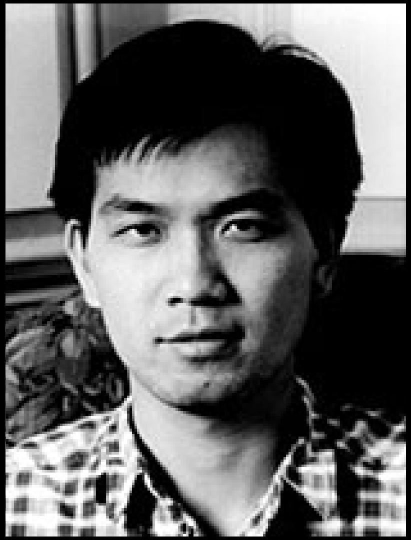
Serendipity, science, and engineering

Engineering sophomore forum
Cambridge, MA, 7 February 2011

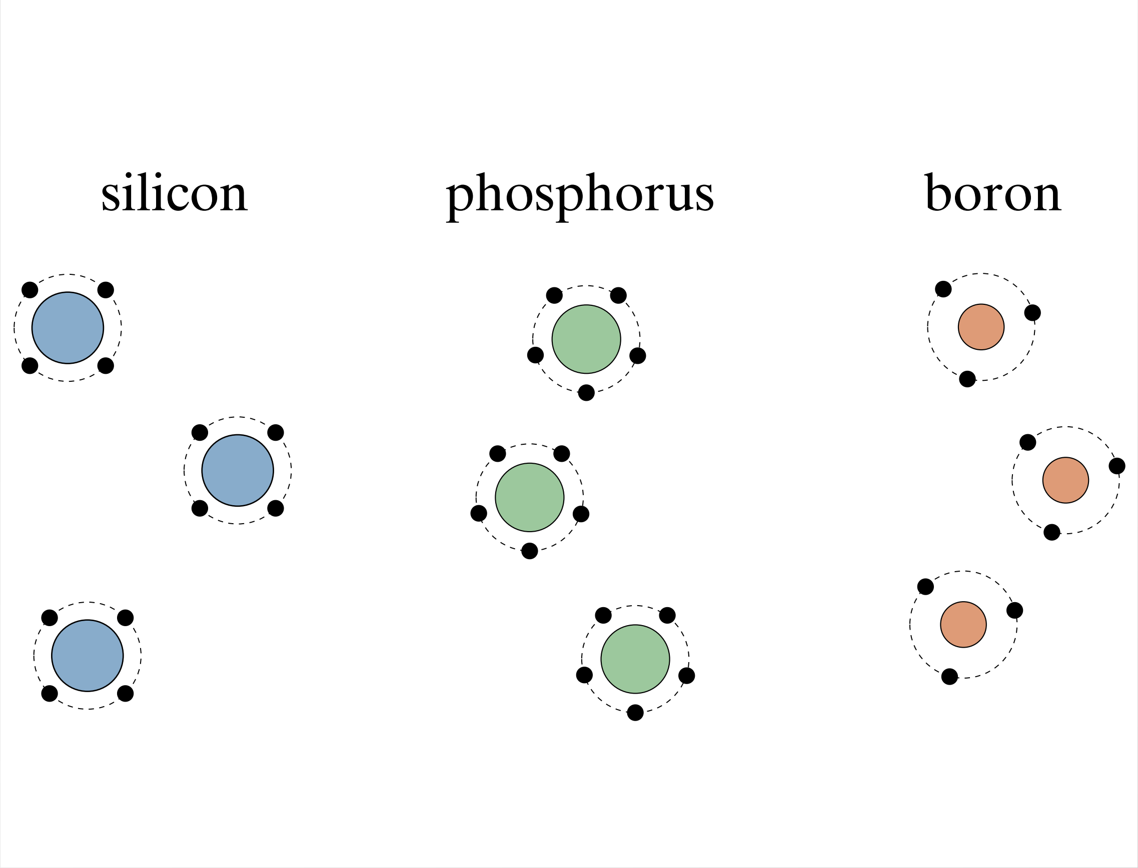
Eric Mazur



Tsing-Hua Her

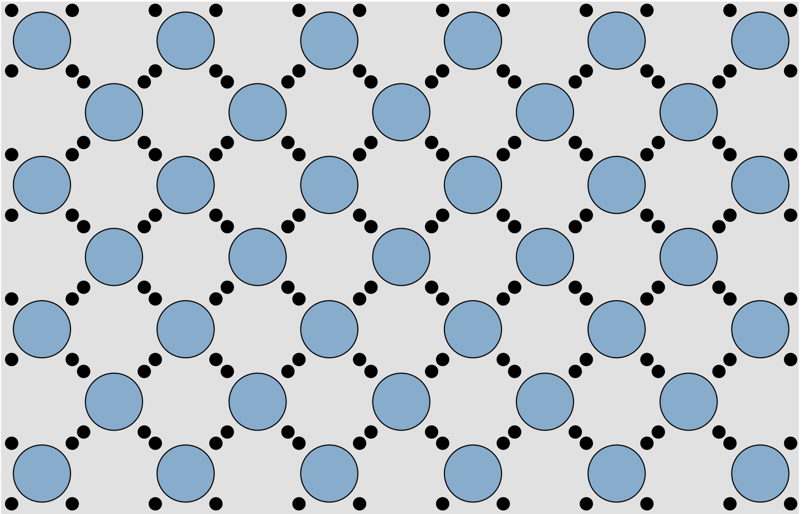
Jim Carey

Introduction



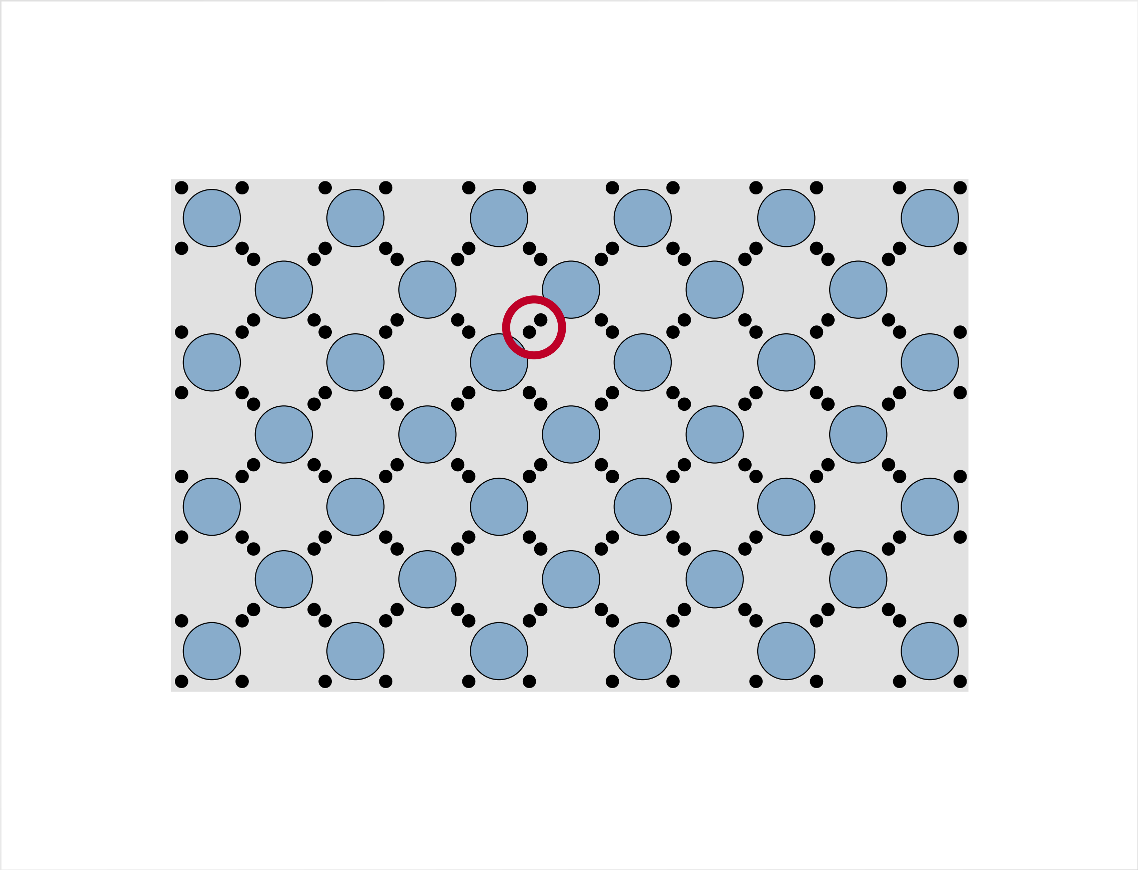
outer ("valence") electrons determine electronic properties

Introduction



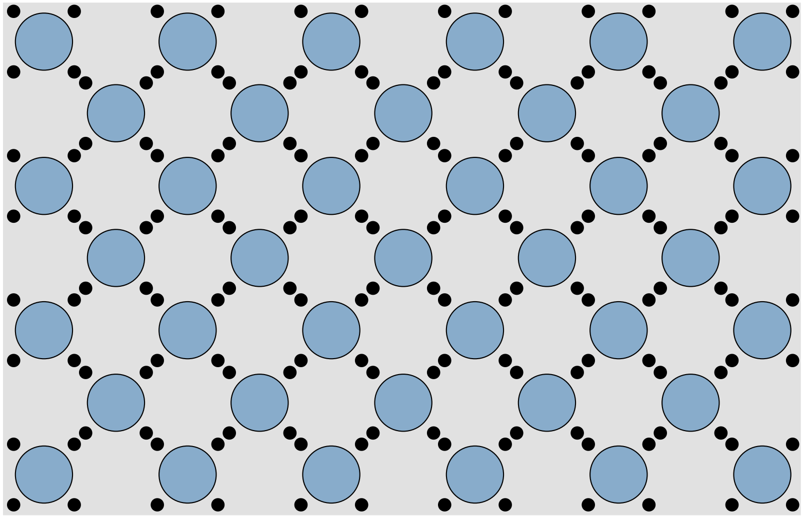
pure (“intrinsic”) silicon

Introduction



electrons in covalent bond are immobile

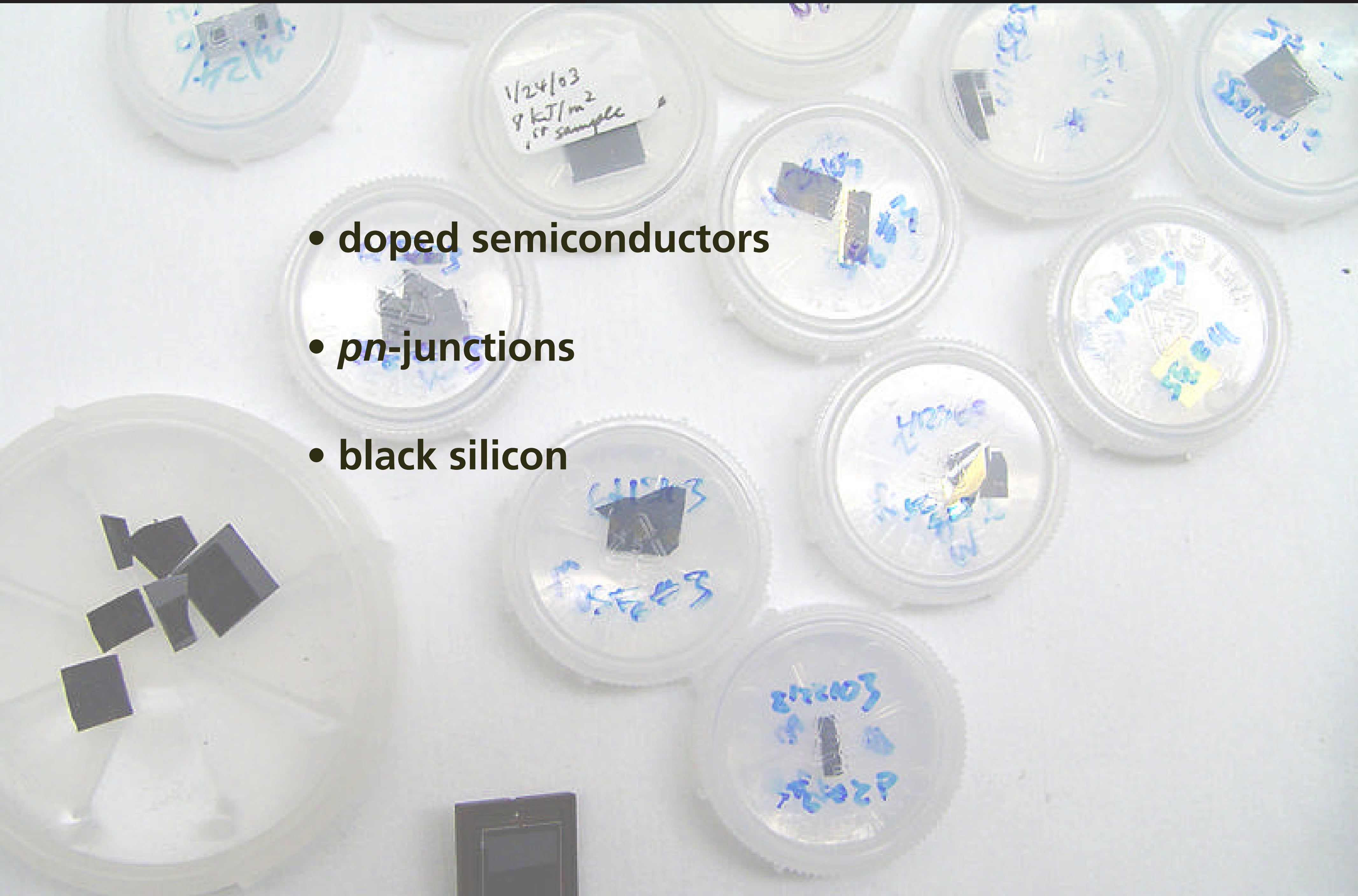
Introduction



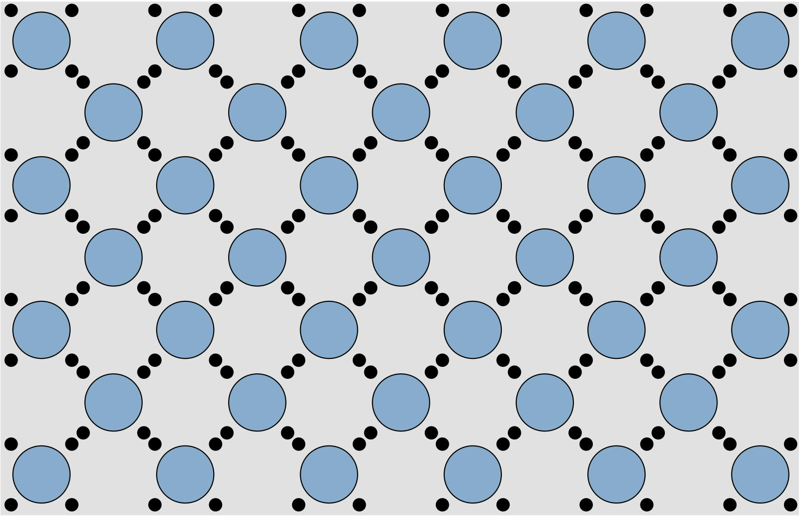
all electrons bound, so no conduction

Outline

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

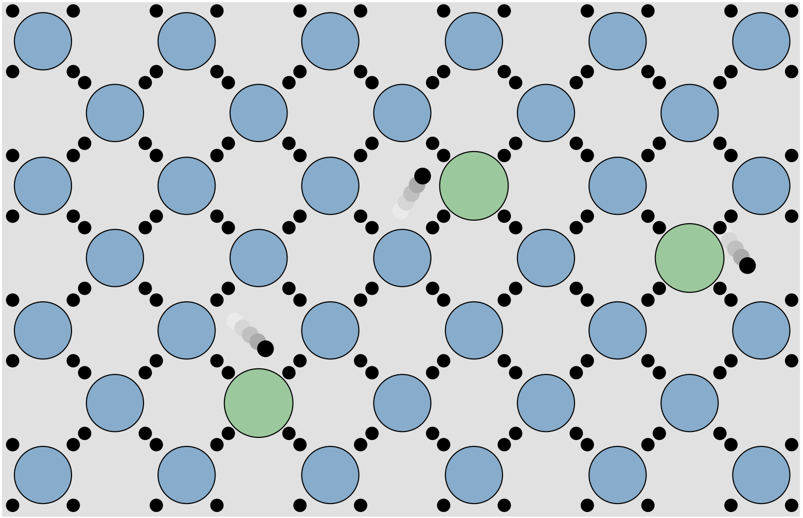


Doped semiconductors



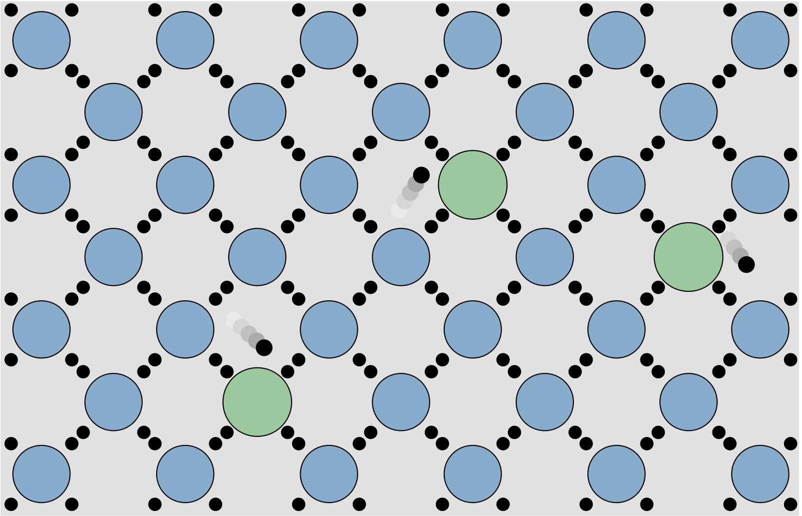
intrinsic silicon: no conduction

Doped semiconductors



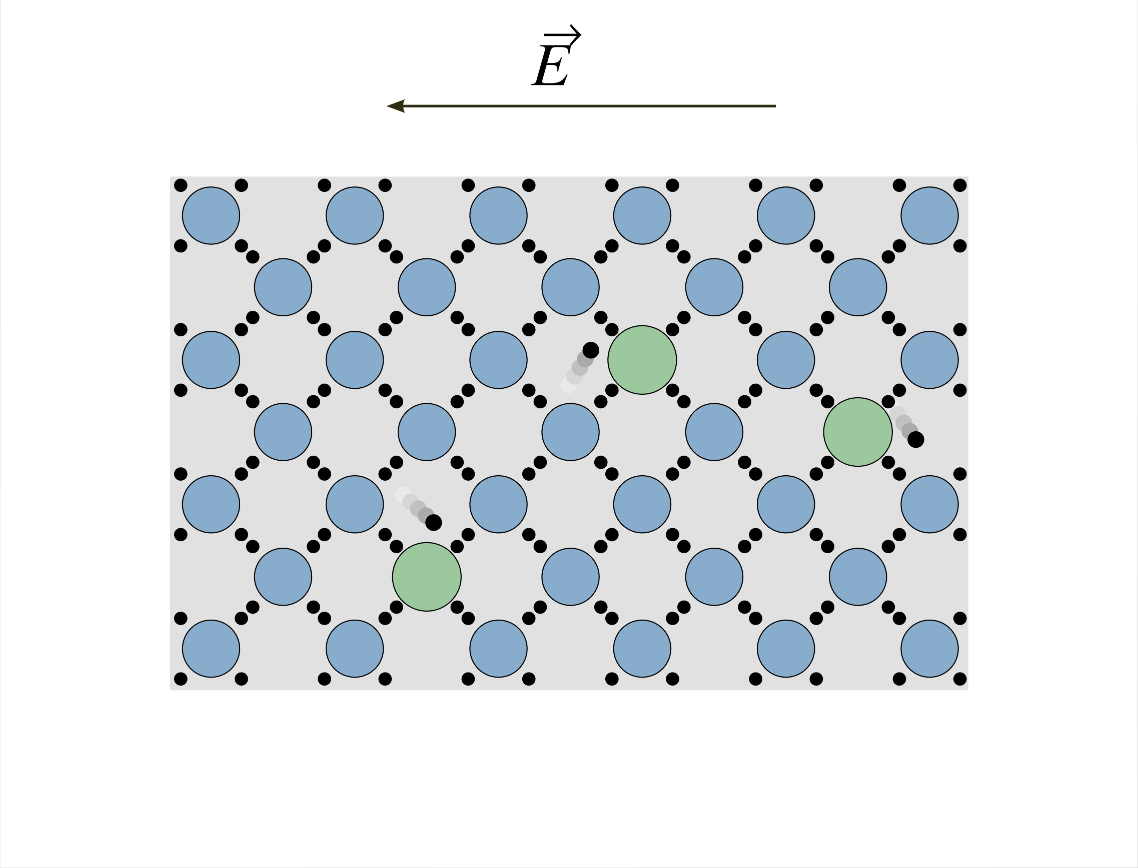
substitute phosphorous: surplus of (free) electrons

Doped semiconductors



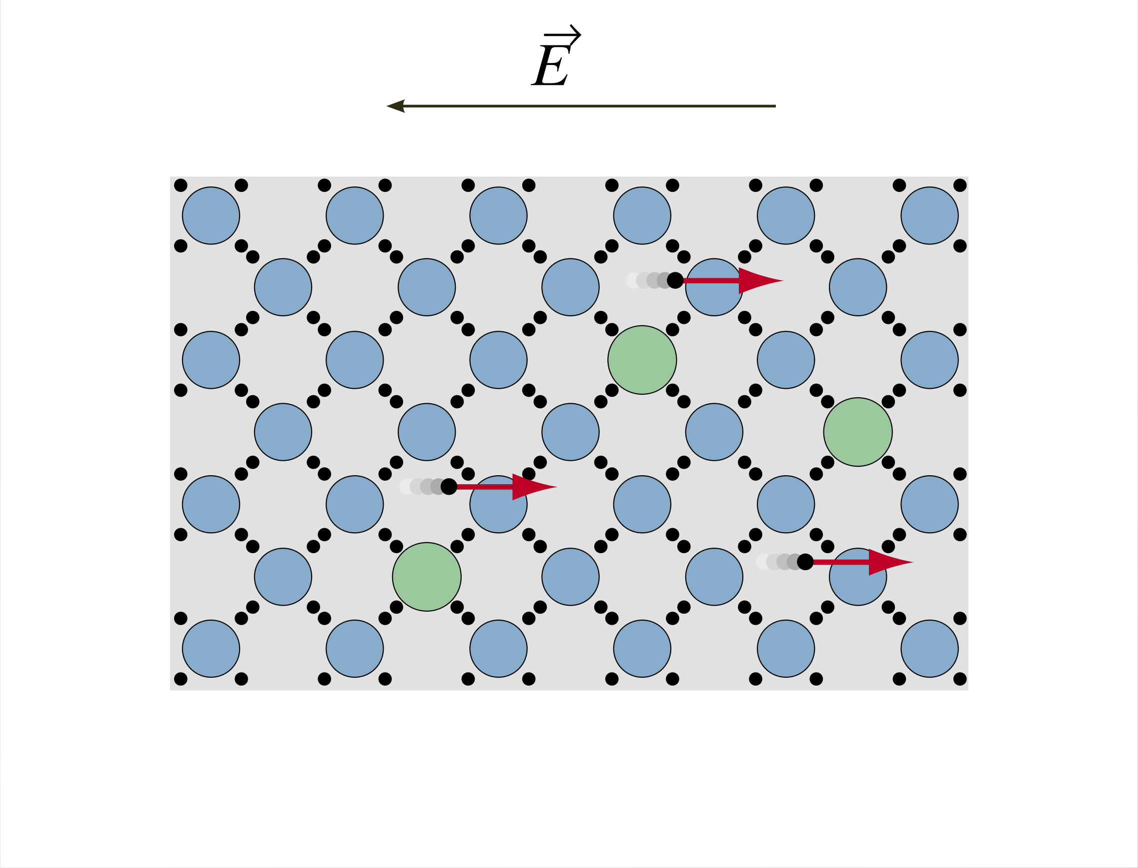
(but material as a whole still neutral!)

Doped semiconductors



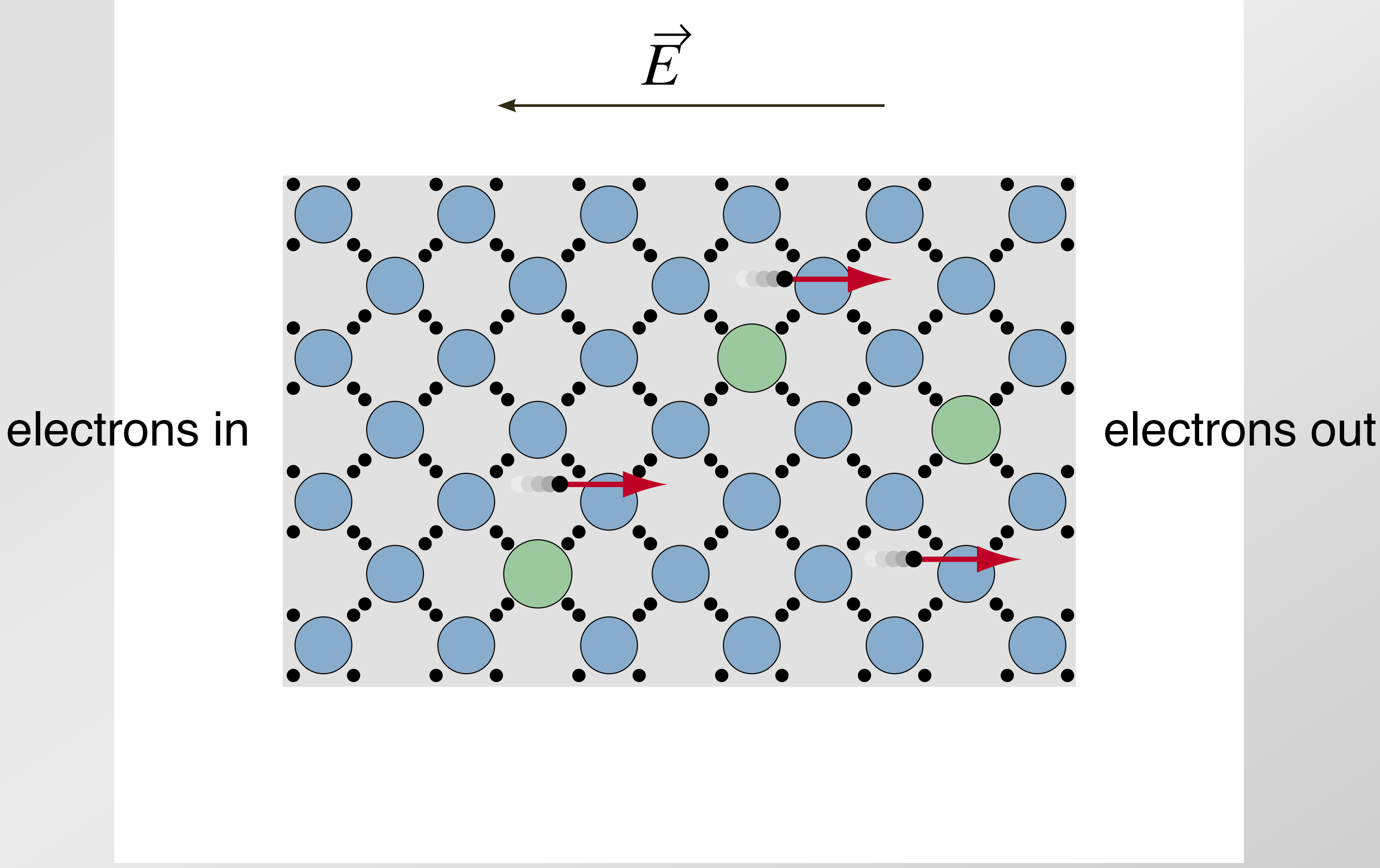
apply electric field…

Doped semiconductors



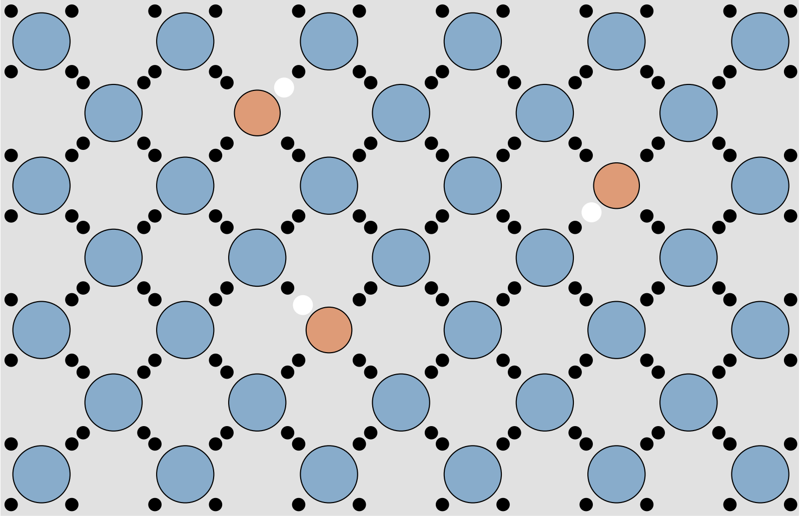
…free electrons lead to conduction

Doped semiconductors



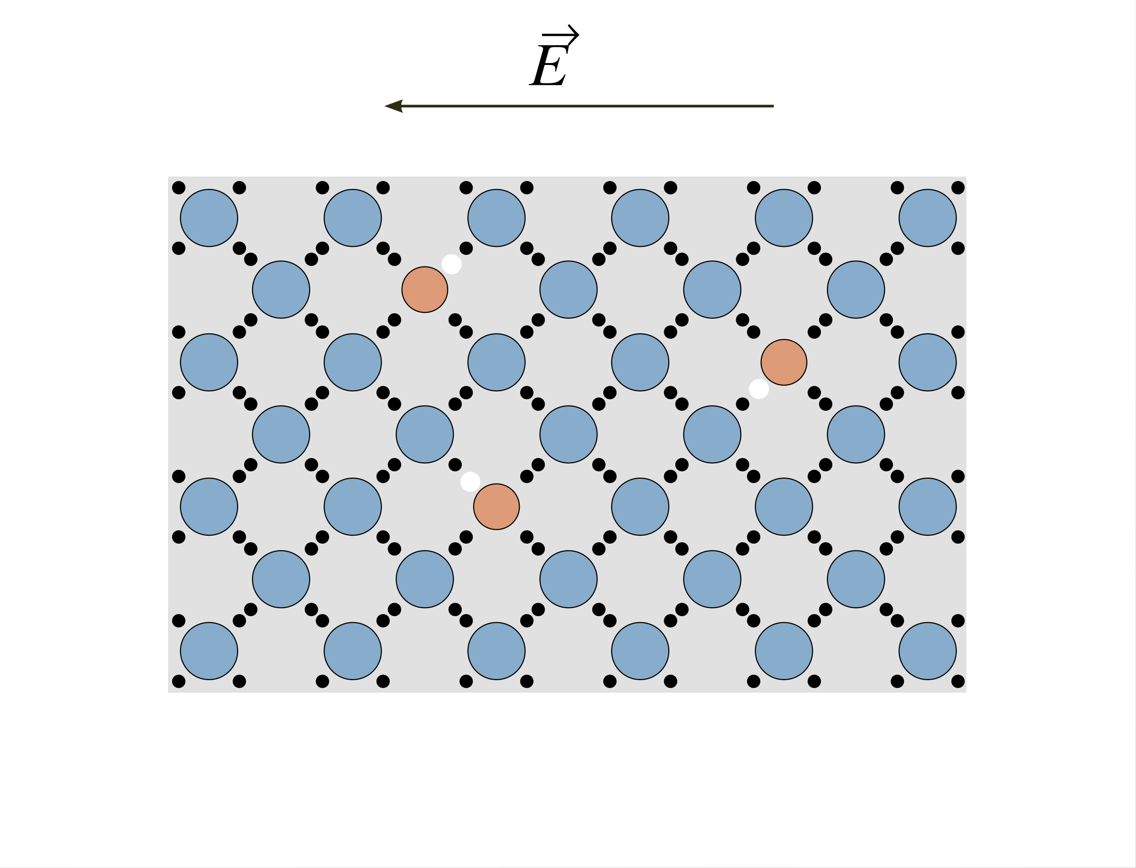
…free electrons lead to conduction

Doped semiconductors



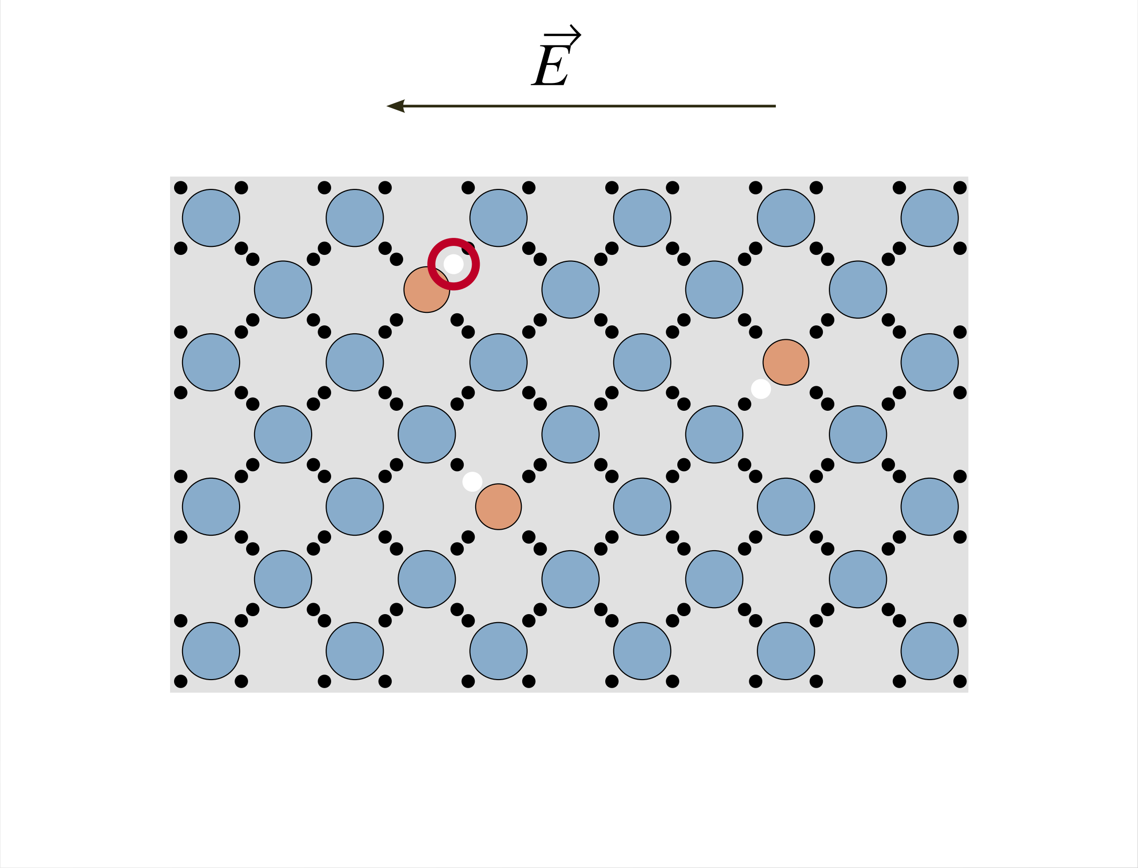
substitute boron: deficit of electrons leaves “holes”

Doped semiconductors



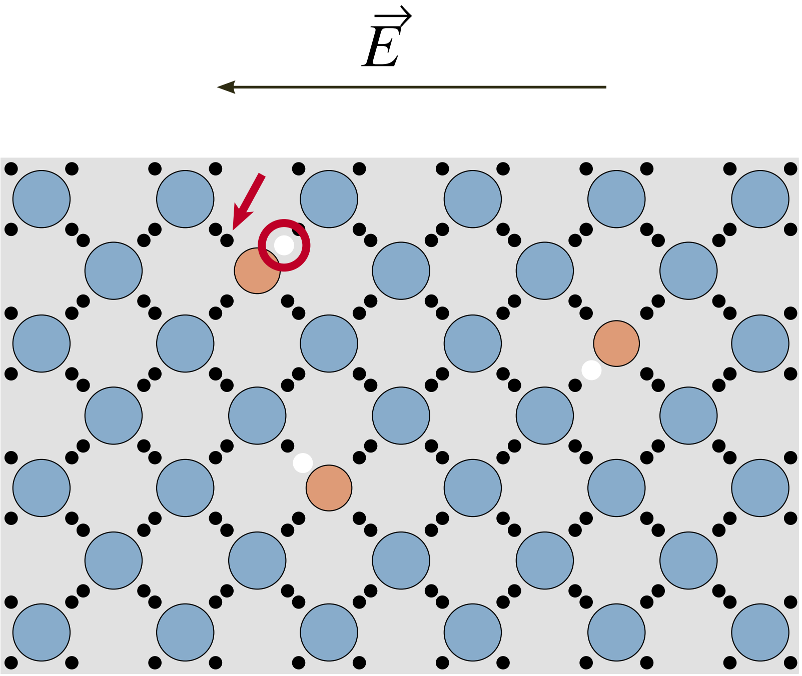
apply electric field…

Doped semiconductors



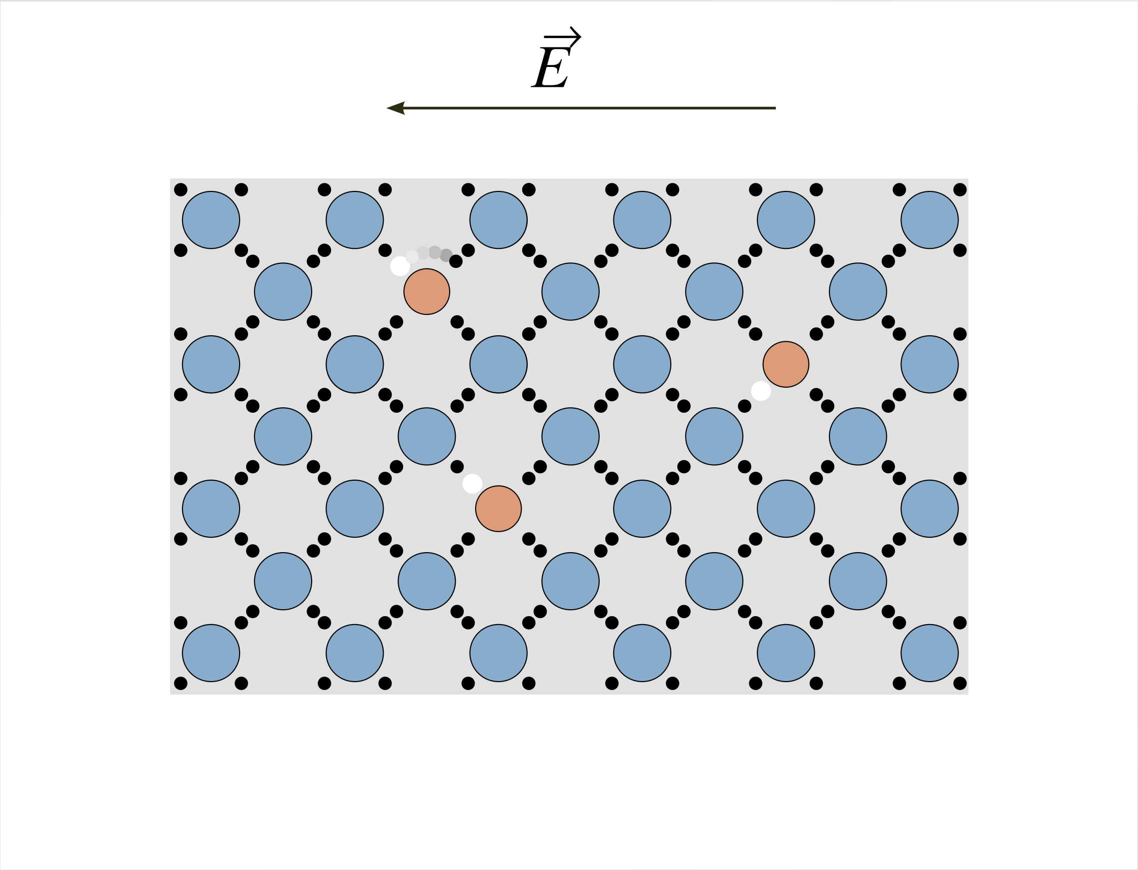
…presence of holes leads to conduction

Doped semiconductors



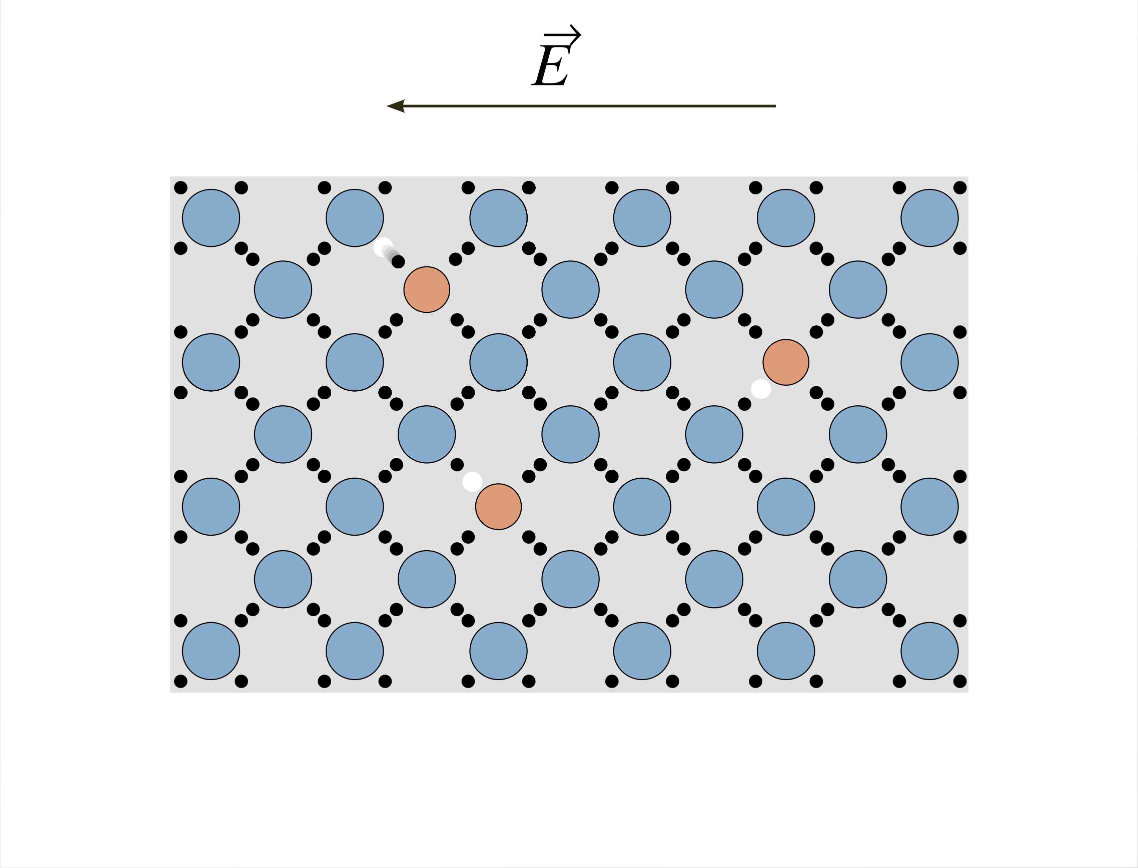
…presence of holes leads to conduction

Doped semiconductors



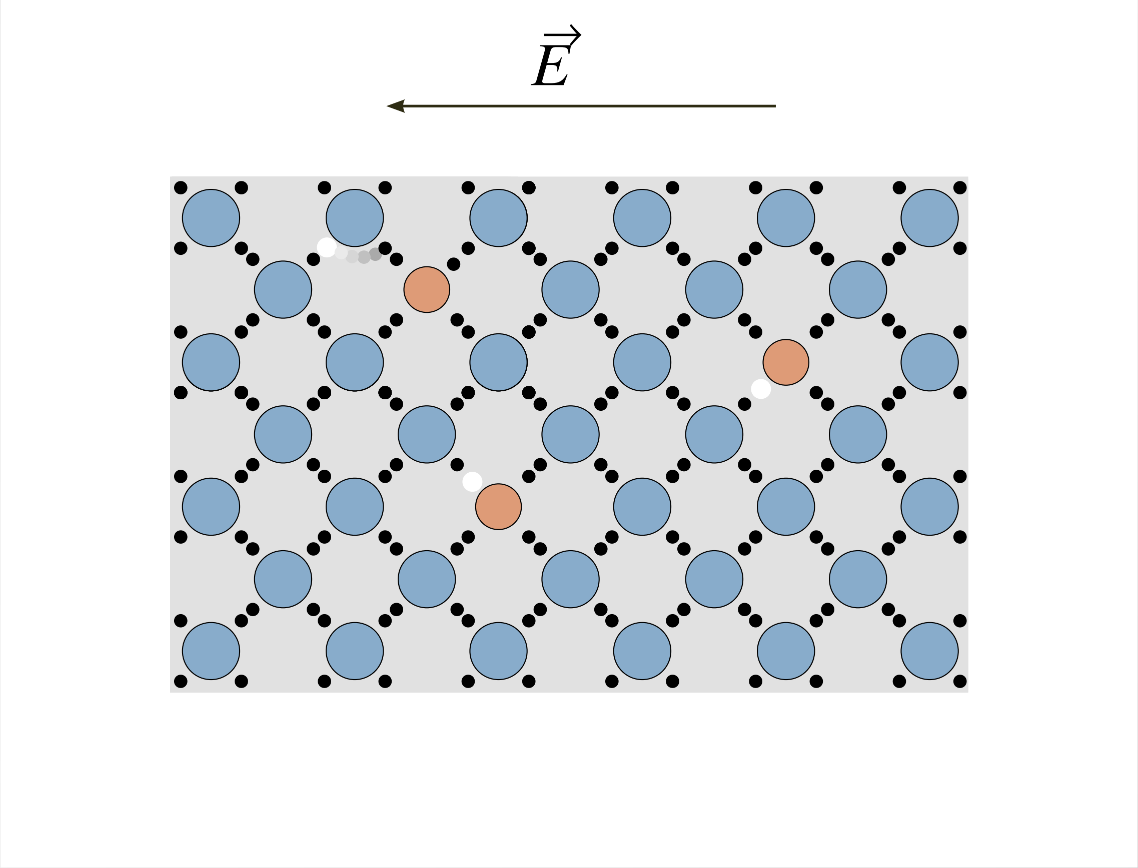
…presence of holes leads to conduction

Doped semiconductors



…presence of holes leads to conduction

Doped semiconductors



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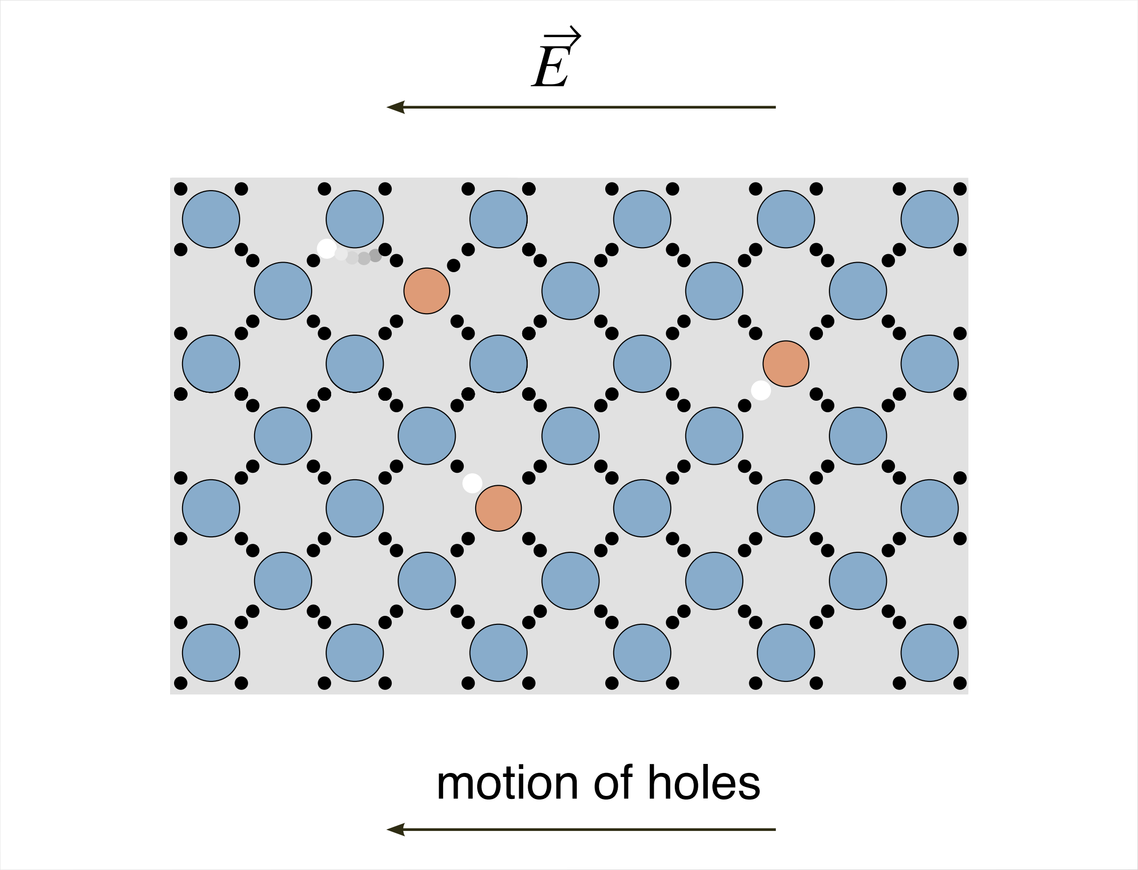
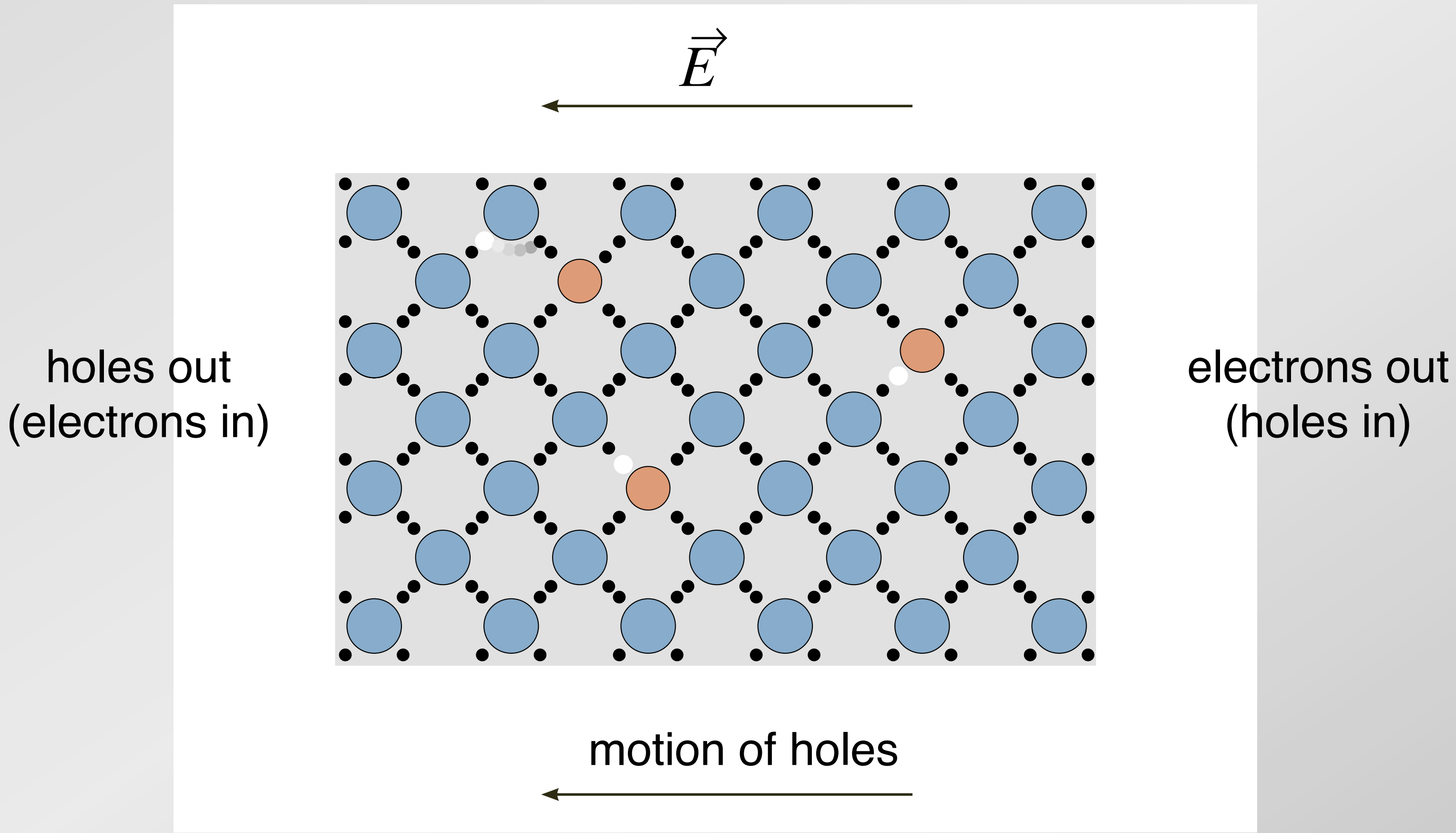
Doped semiconductors



holes are like positively charged particles

Doped semiconductors



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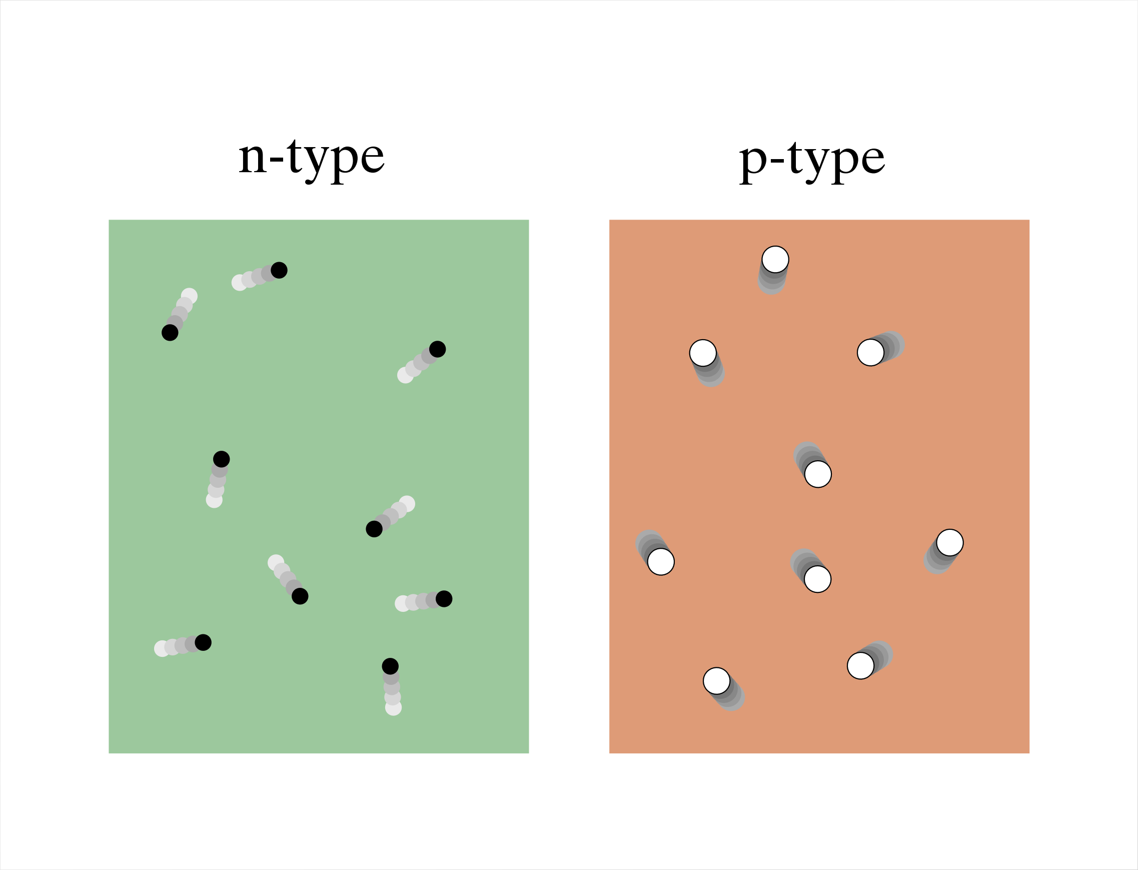
Doped semiconductors

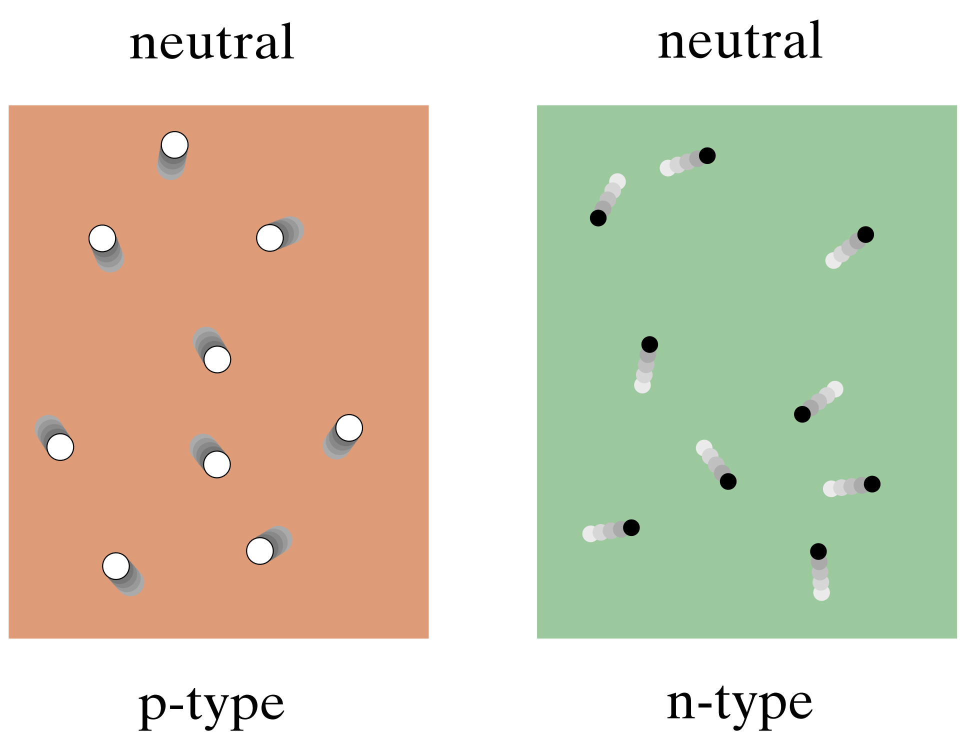


simplify representation

Outline

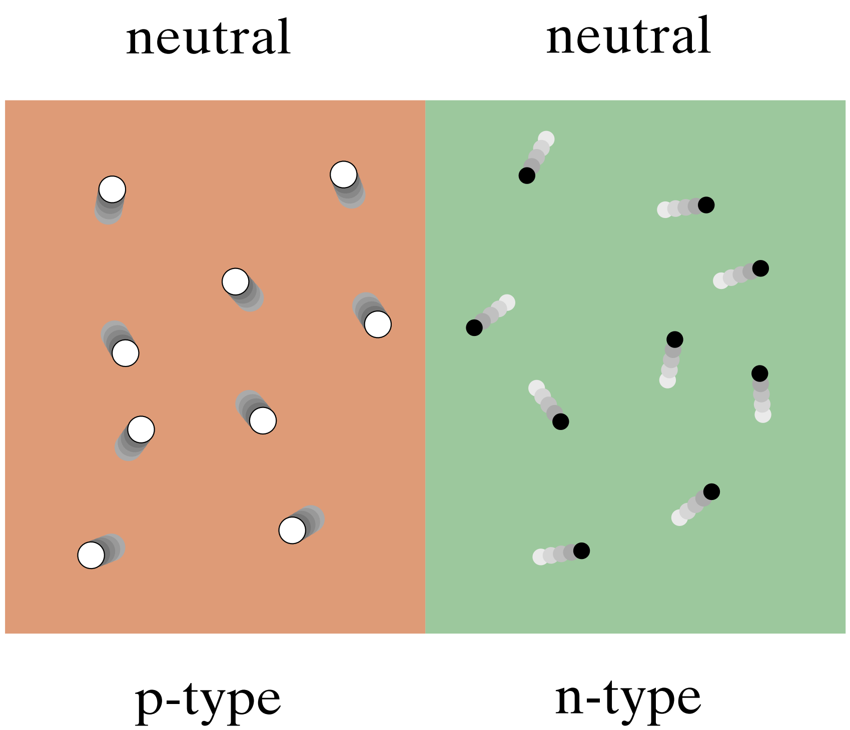
- doped semiconductors
- *pn*-junctions
- black silicon

pn-junctions



bring *p* and *n* materials together…

pn-junctions



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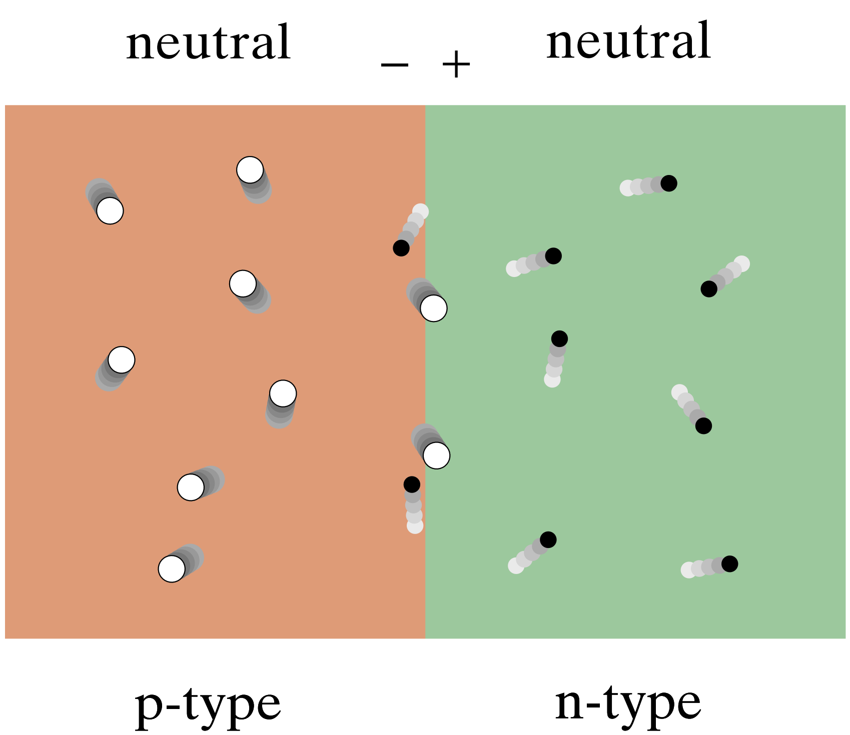
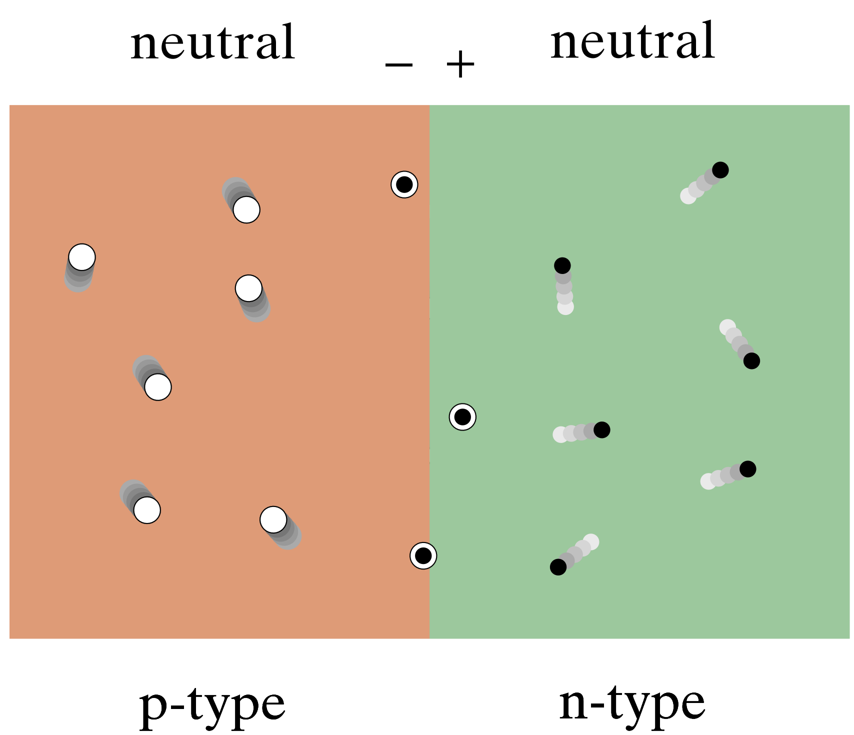


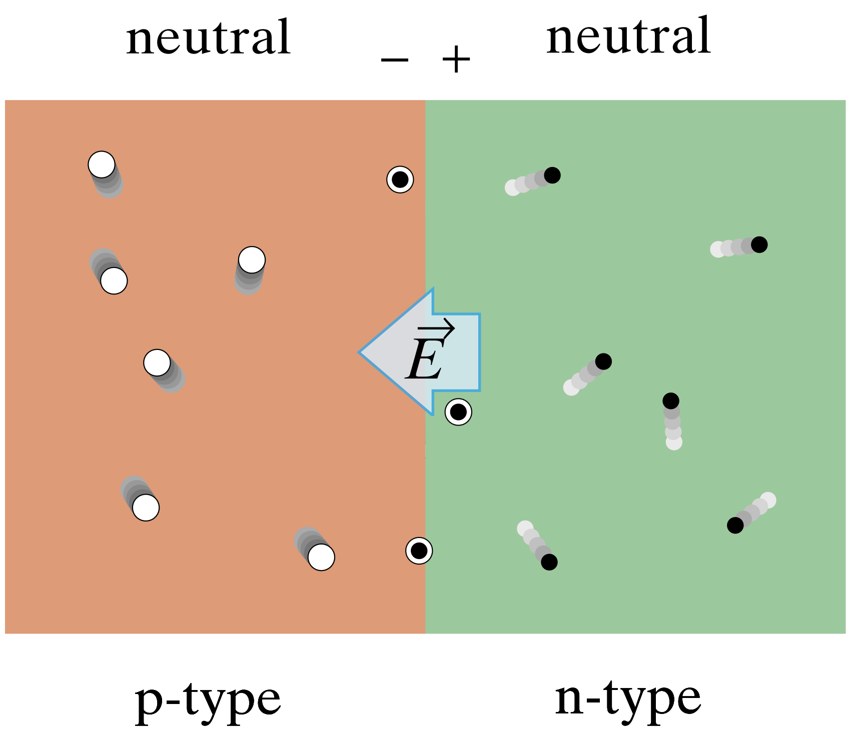
electrons and holes diffuse across junction…

pn-junctions



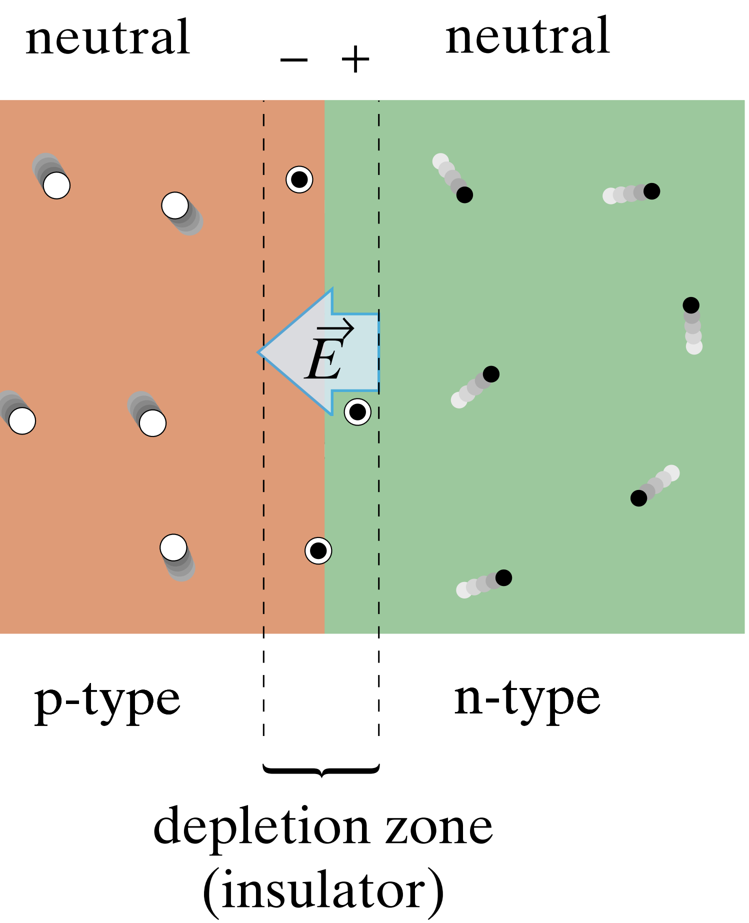
…and get ‘trapped’ after they combine

pn-junctions



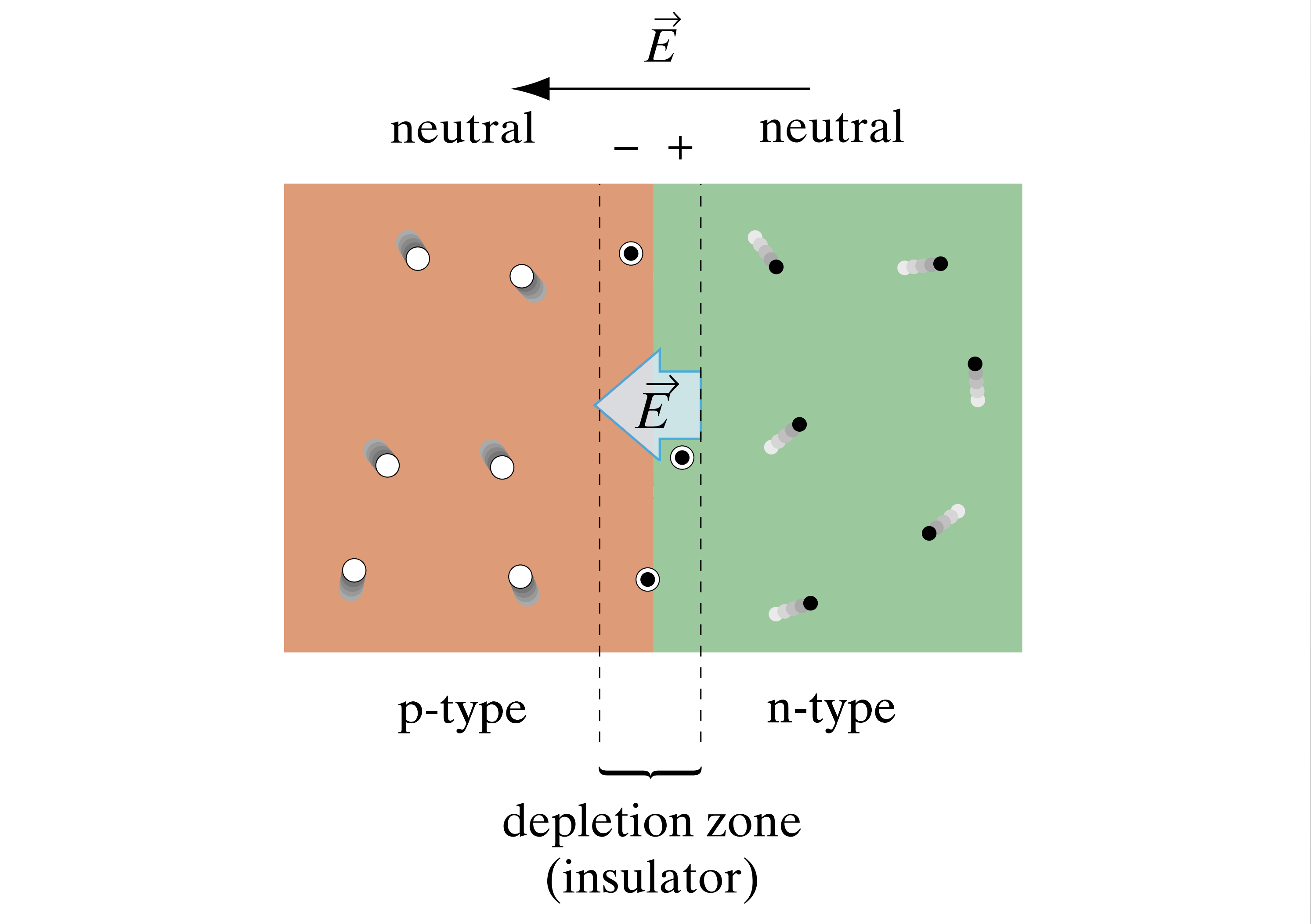
build-up of charge leads to electric field that stops diffusion

pn-junctions



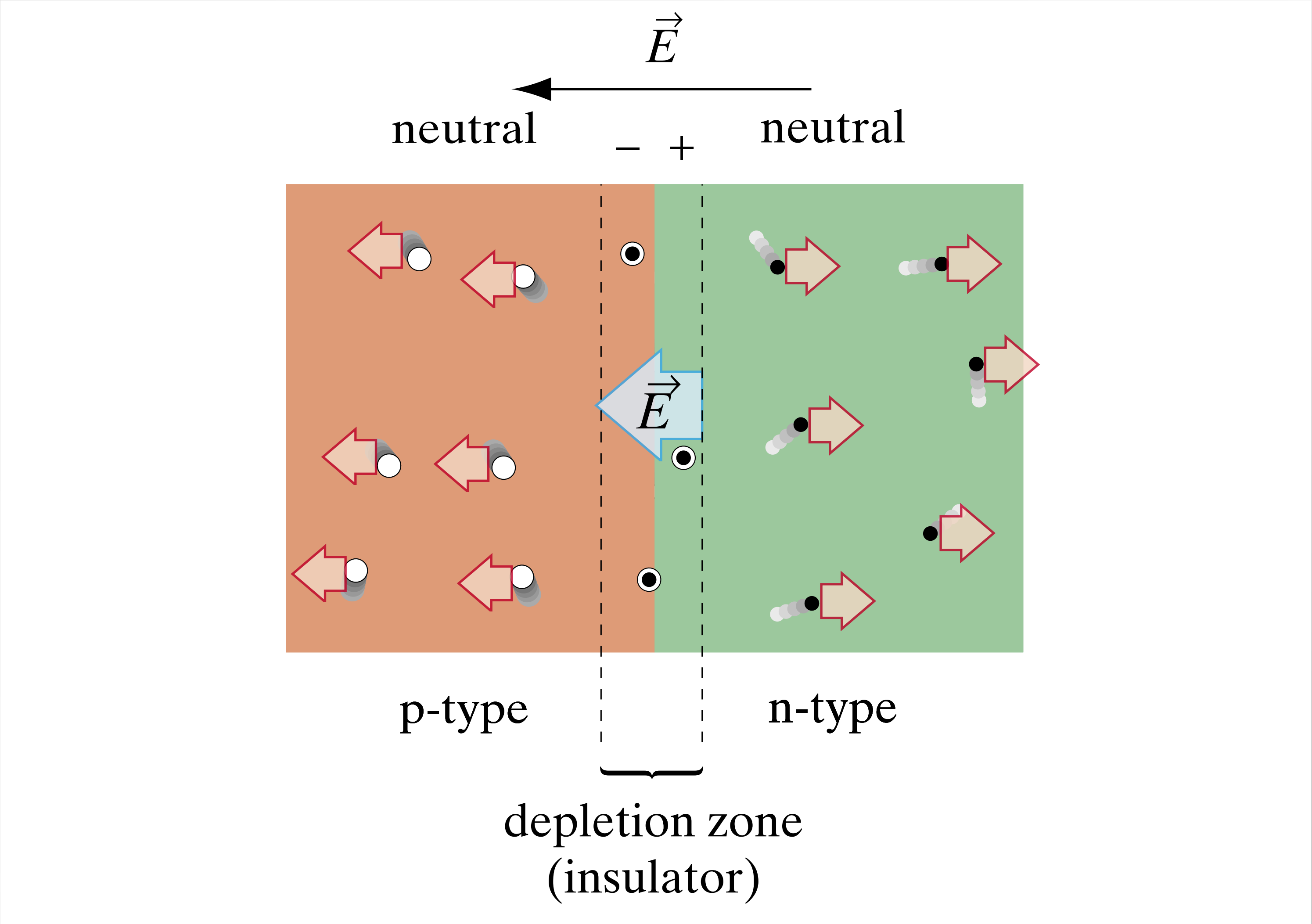
non-conducting layer at junction

pn-junctions



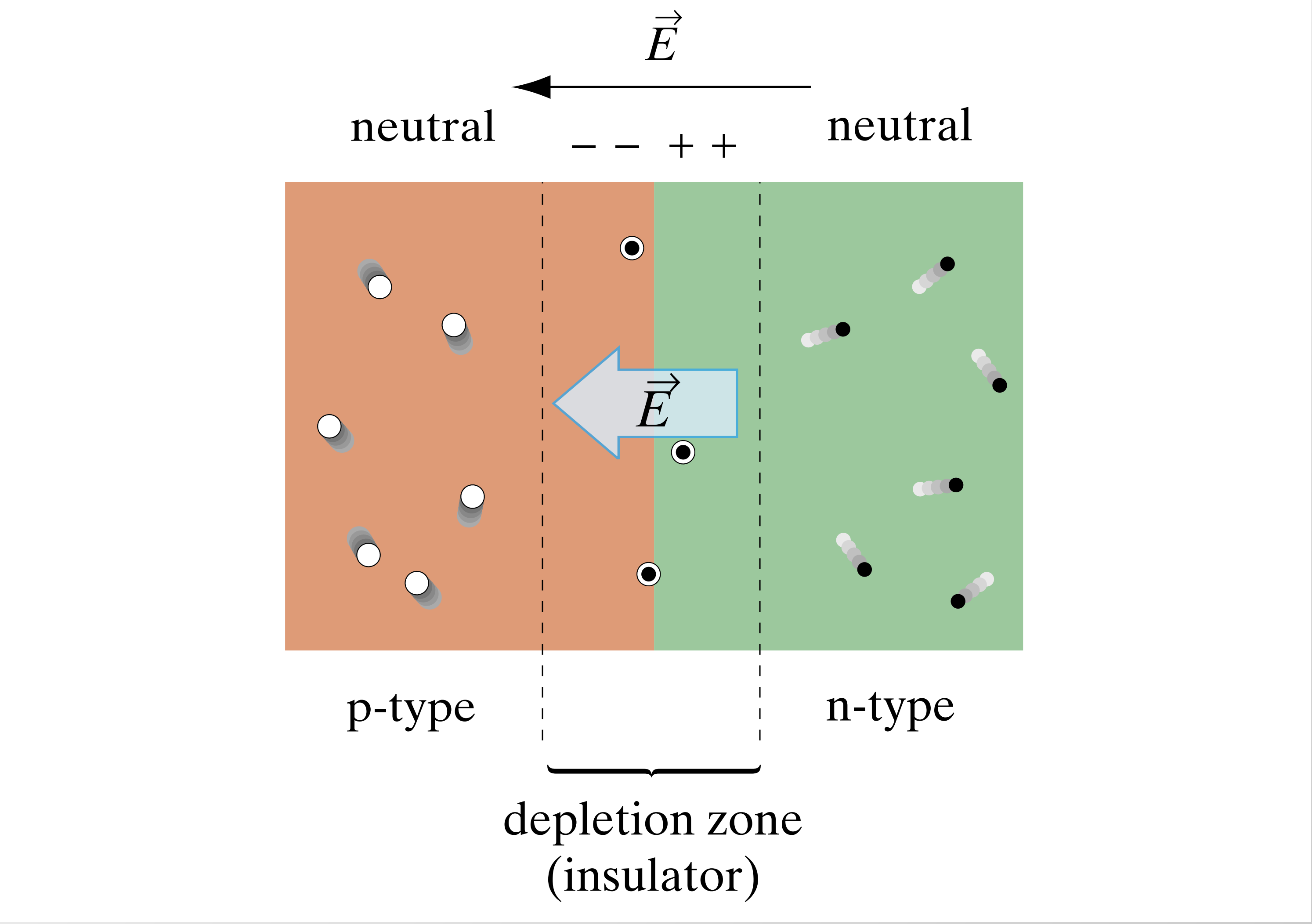
apply electric field…

pn-junctions



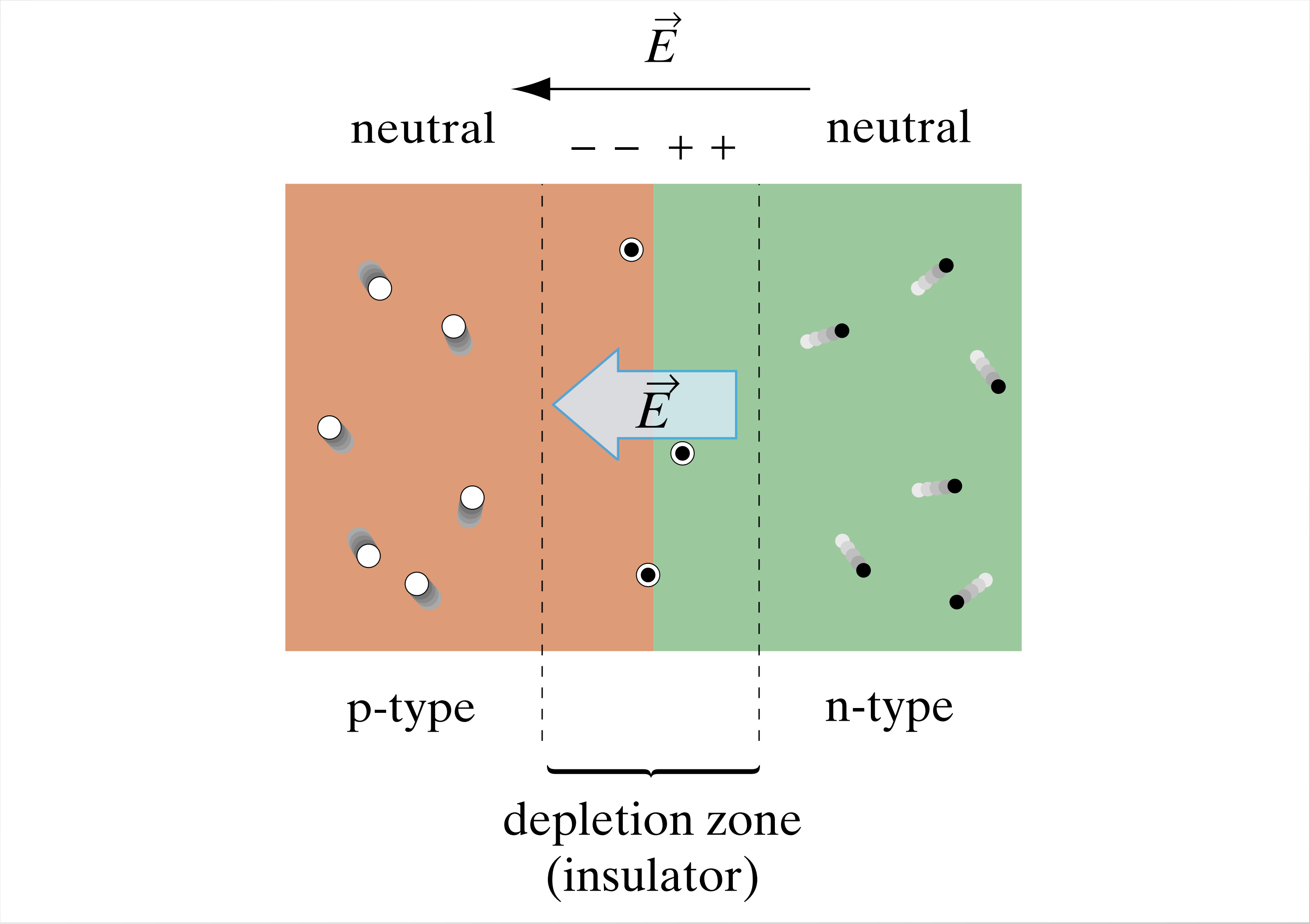
…holes pushed to left, electrons to right…

pn-junctions



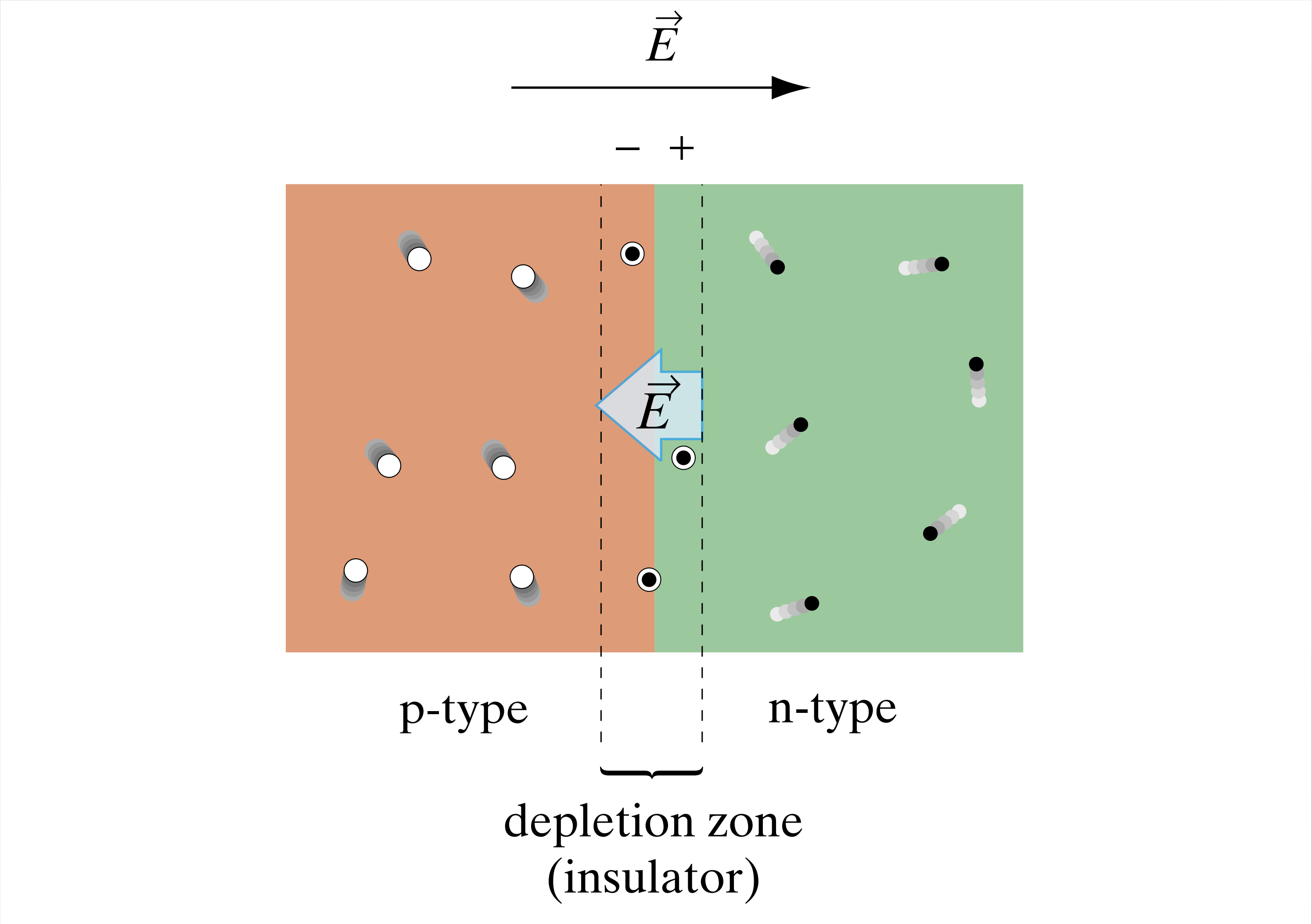
…and so depletion zone expands

pn-junctions



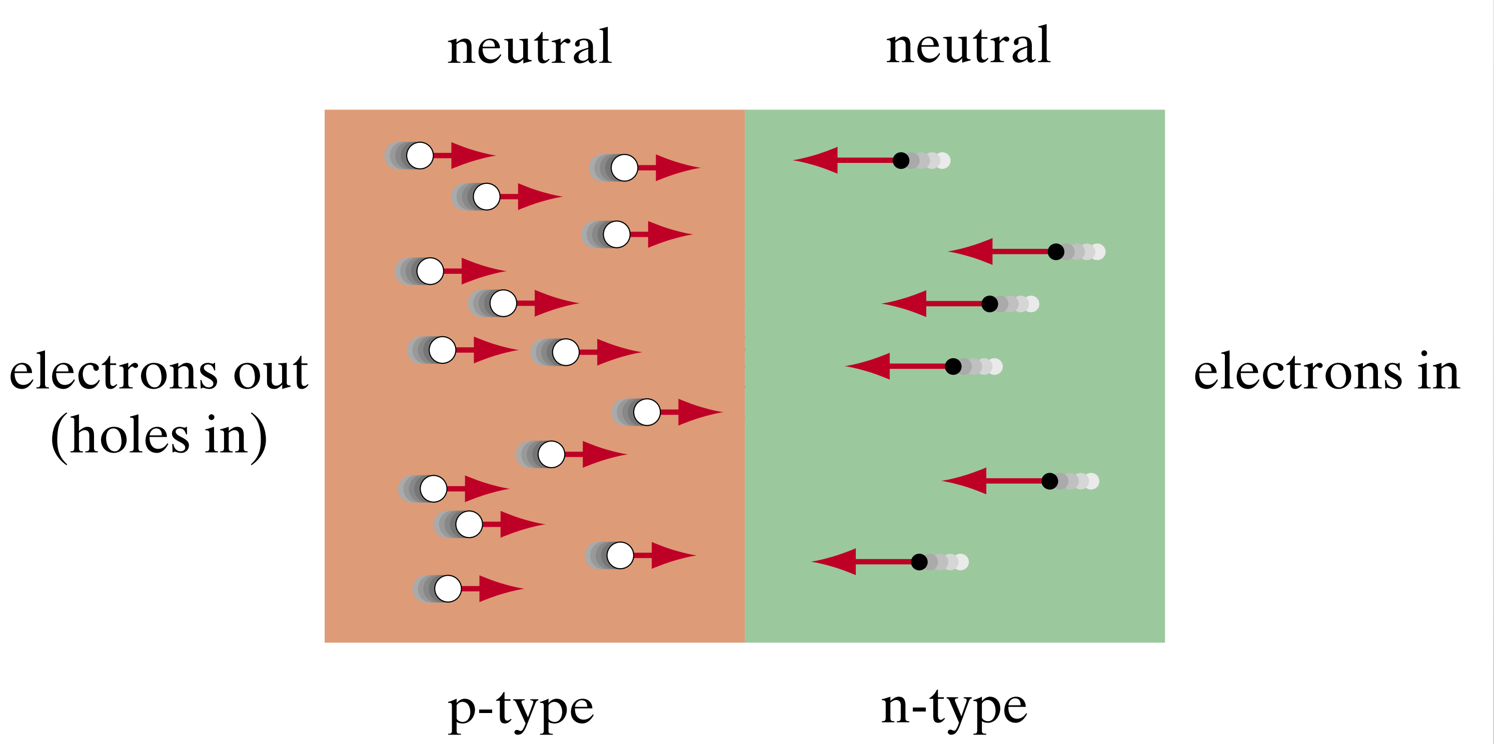
NO conduction

pn-junctions



reverse electric field…

pn-junctions



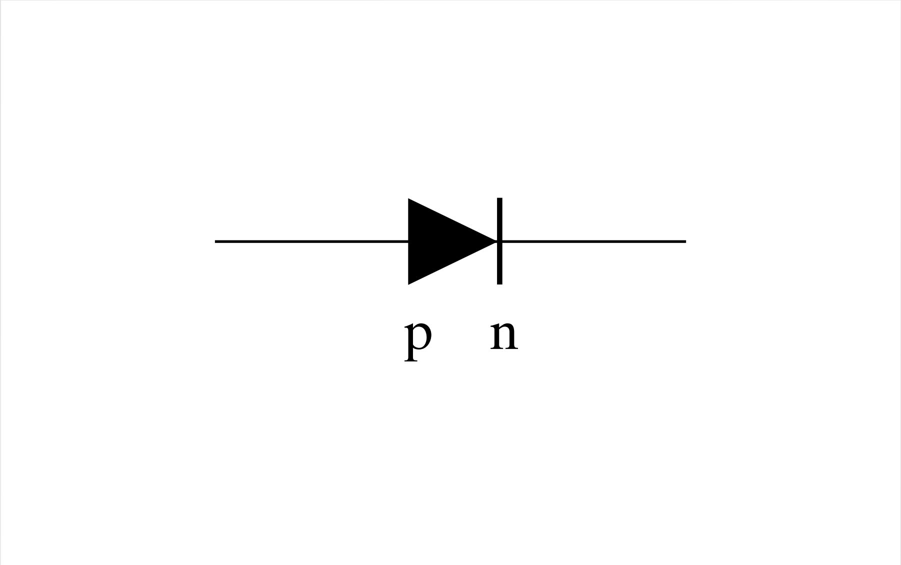
…depletion zone shrinks and current flows

pn-junctions

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

pn-junctions

diode

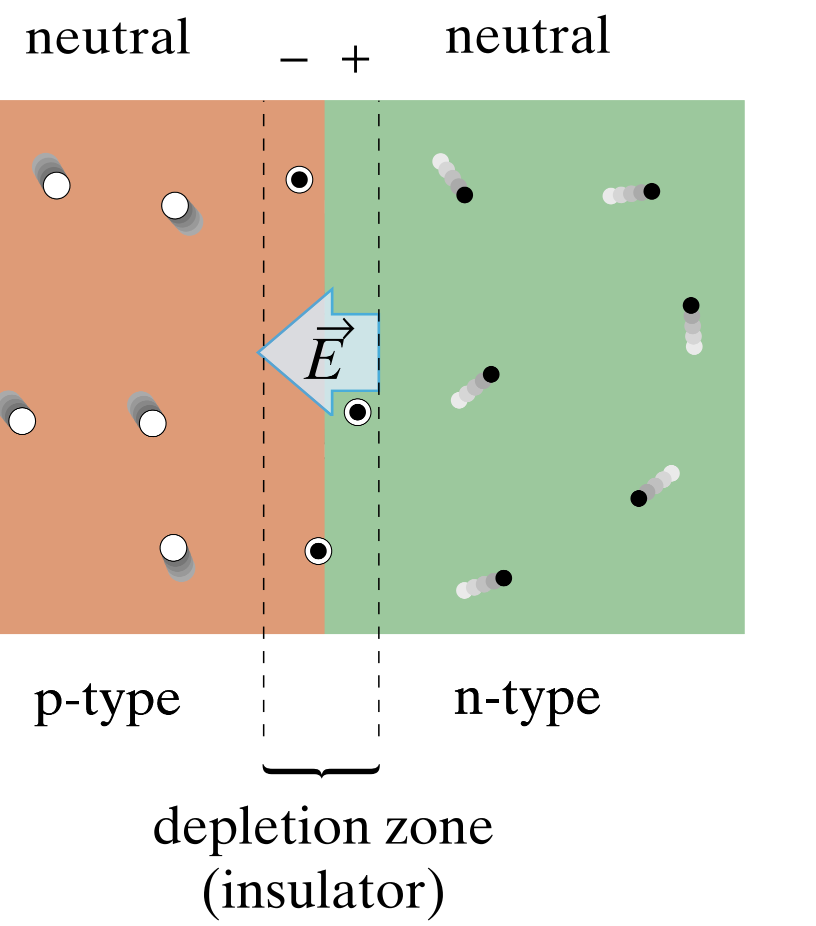


current flows along arrow only (from *p* to *n*)

pn-junctions

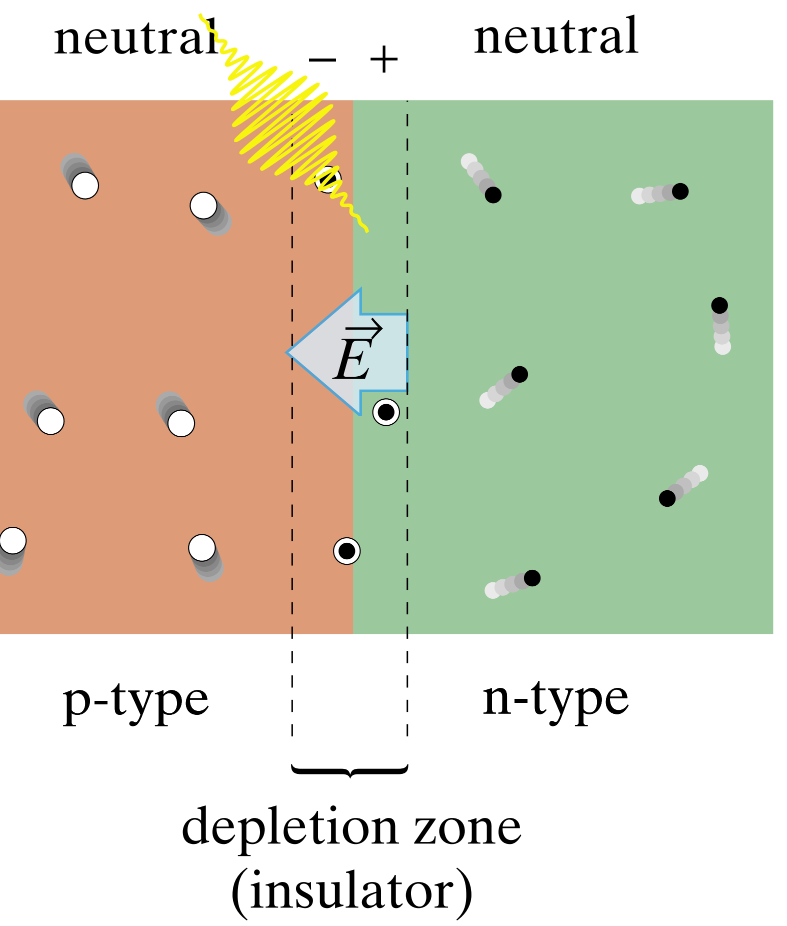
can also be used as a light detector!

pn-junctions



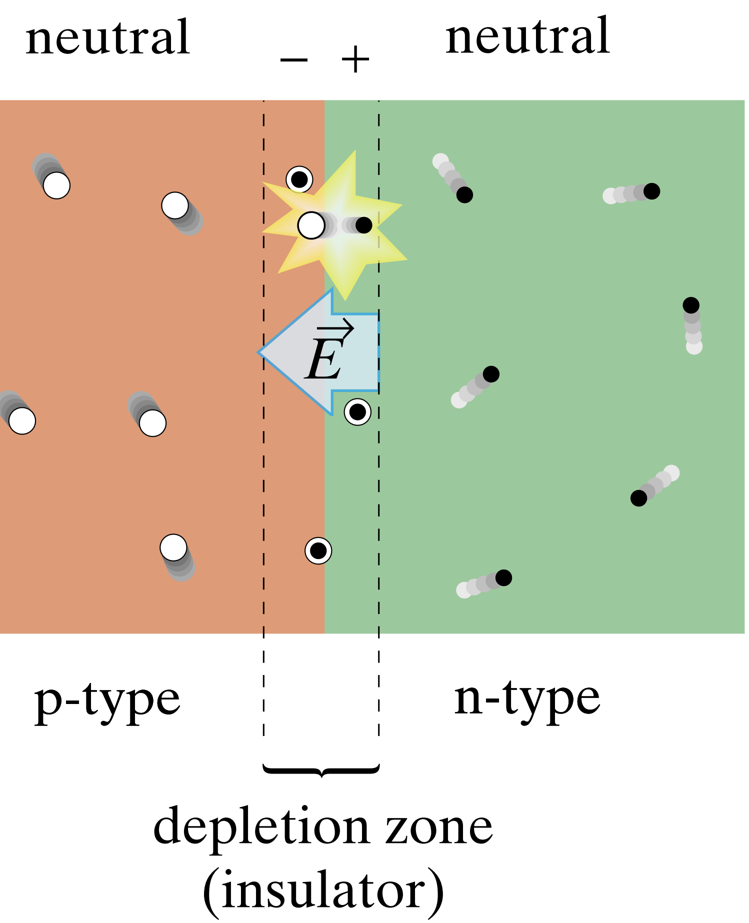
depletion layer can convert light into electric energy

pn-junctions



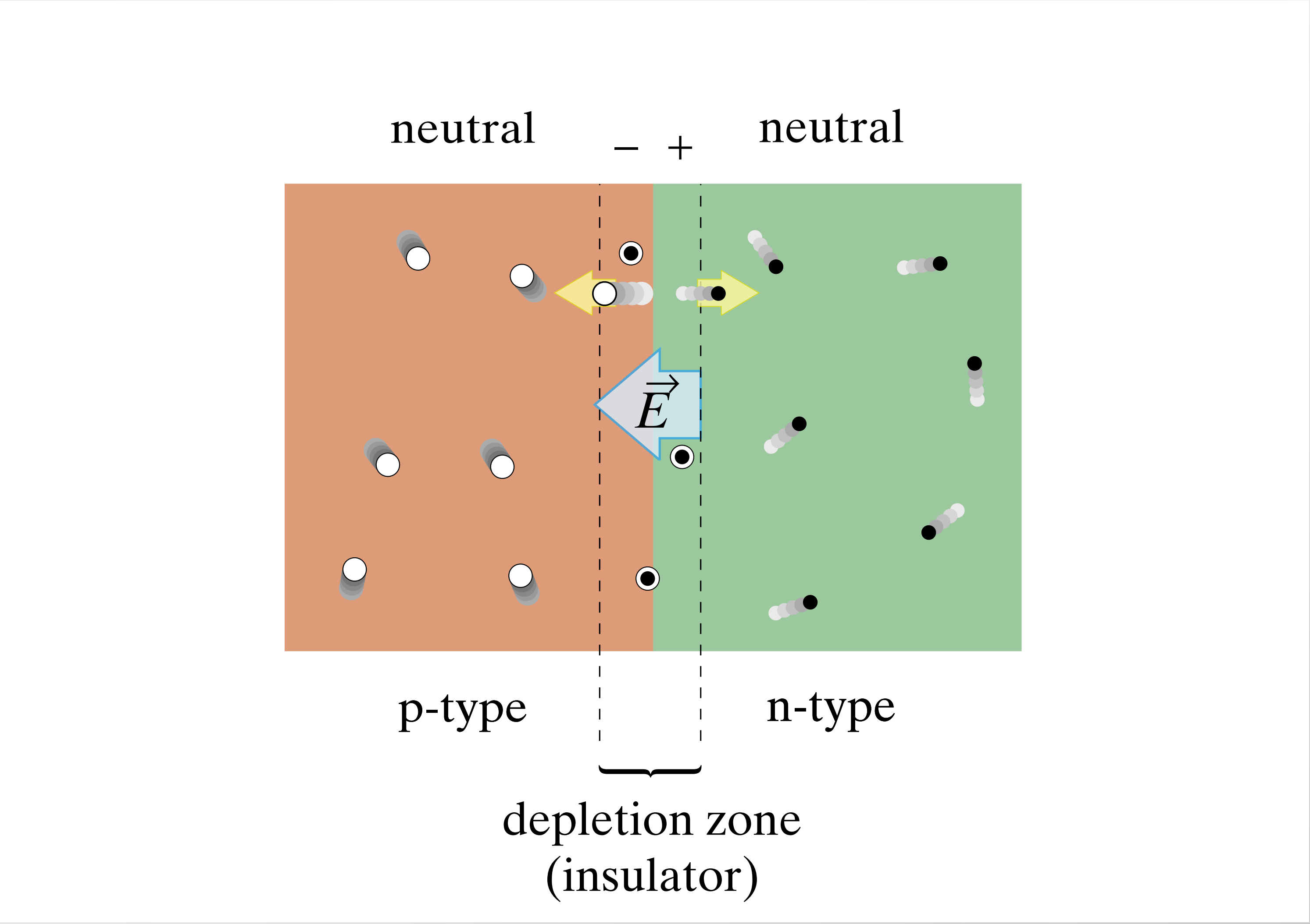
incident photon knocks out electron…

pn-junctions



…creating an electron-hole pair

pn-junctions

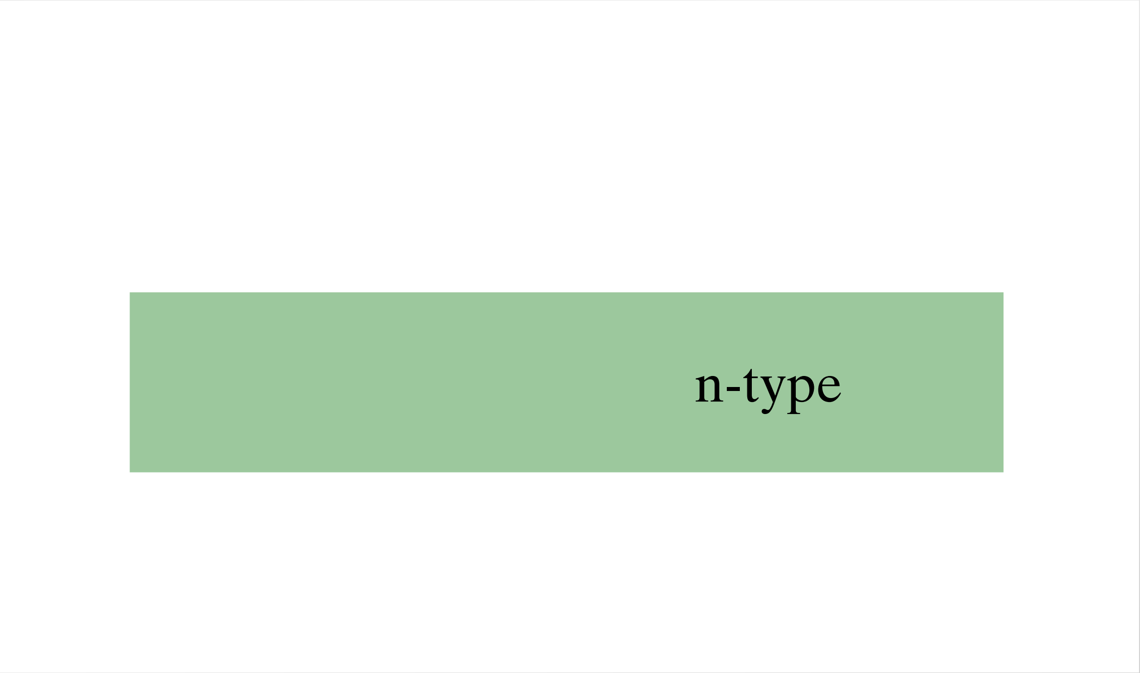


E-field separates eh-pair, causing current

pn-junctions

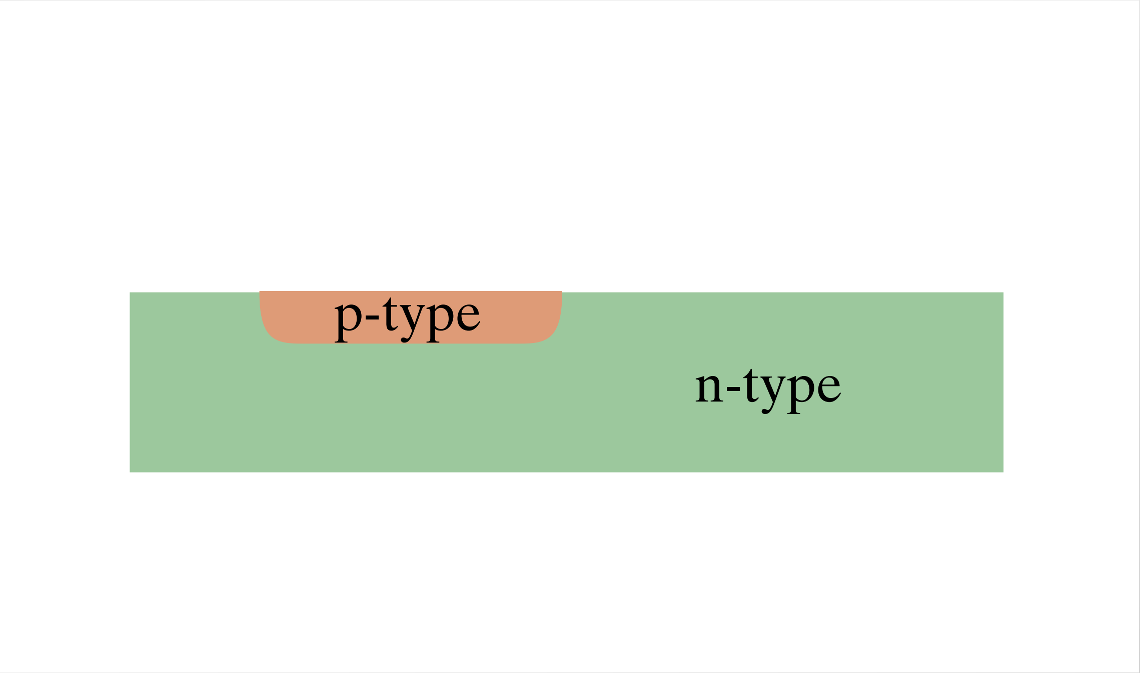
how to make a miniature diode on a chip?

pn-junctions



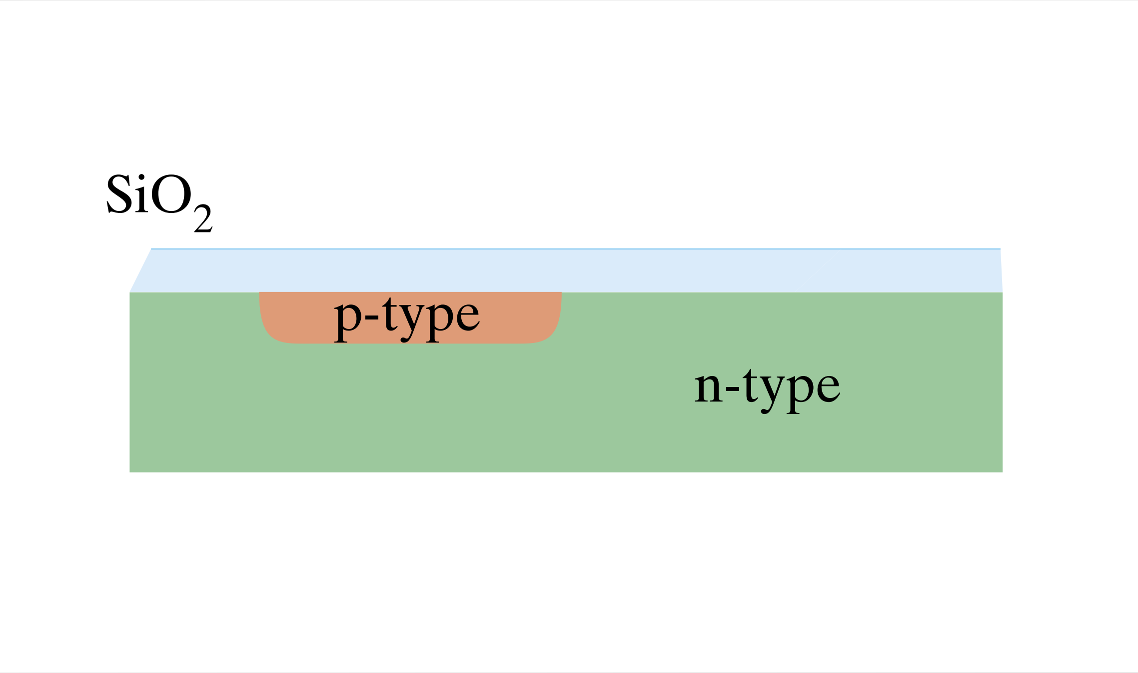
begin with an *n*-doped wafer

pn-junctions



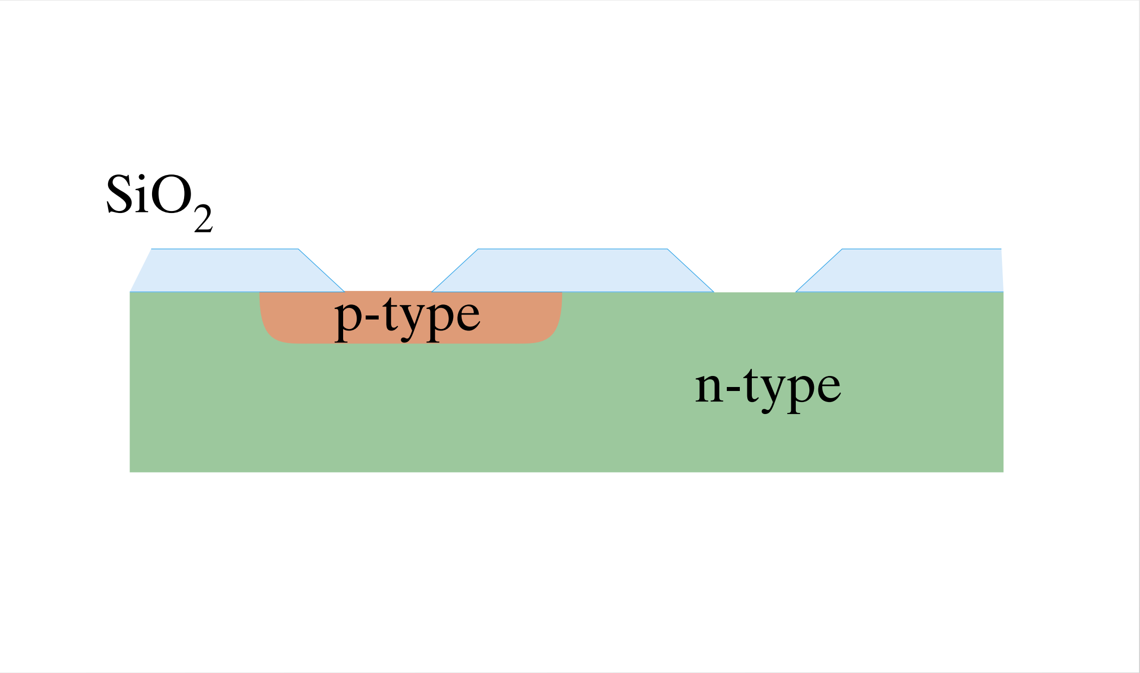
***p*-dope small region**

pn-junctions



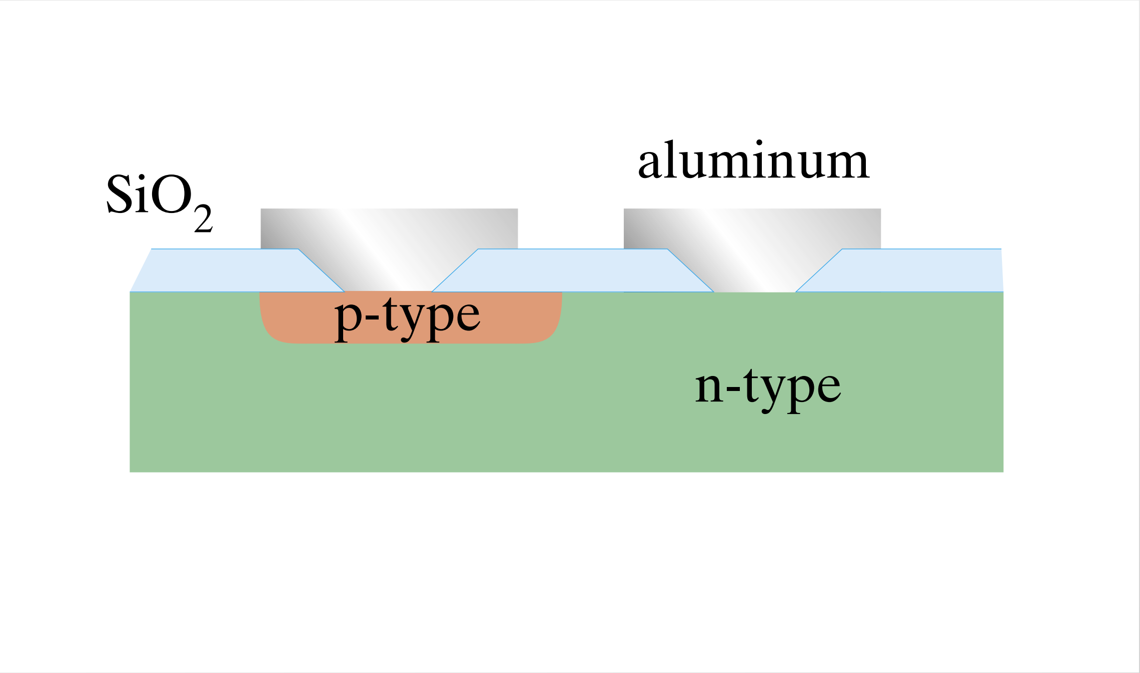
cover with insulating layer

pn-junctions



etch insulating layer

pn-junctions

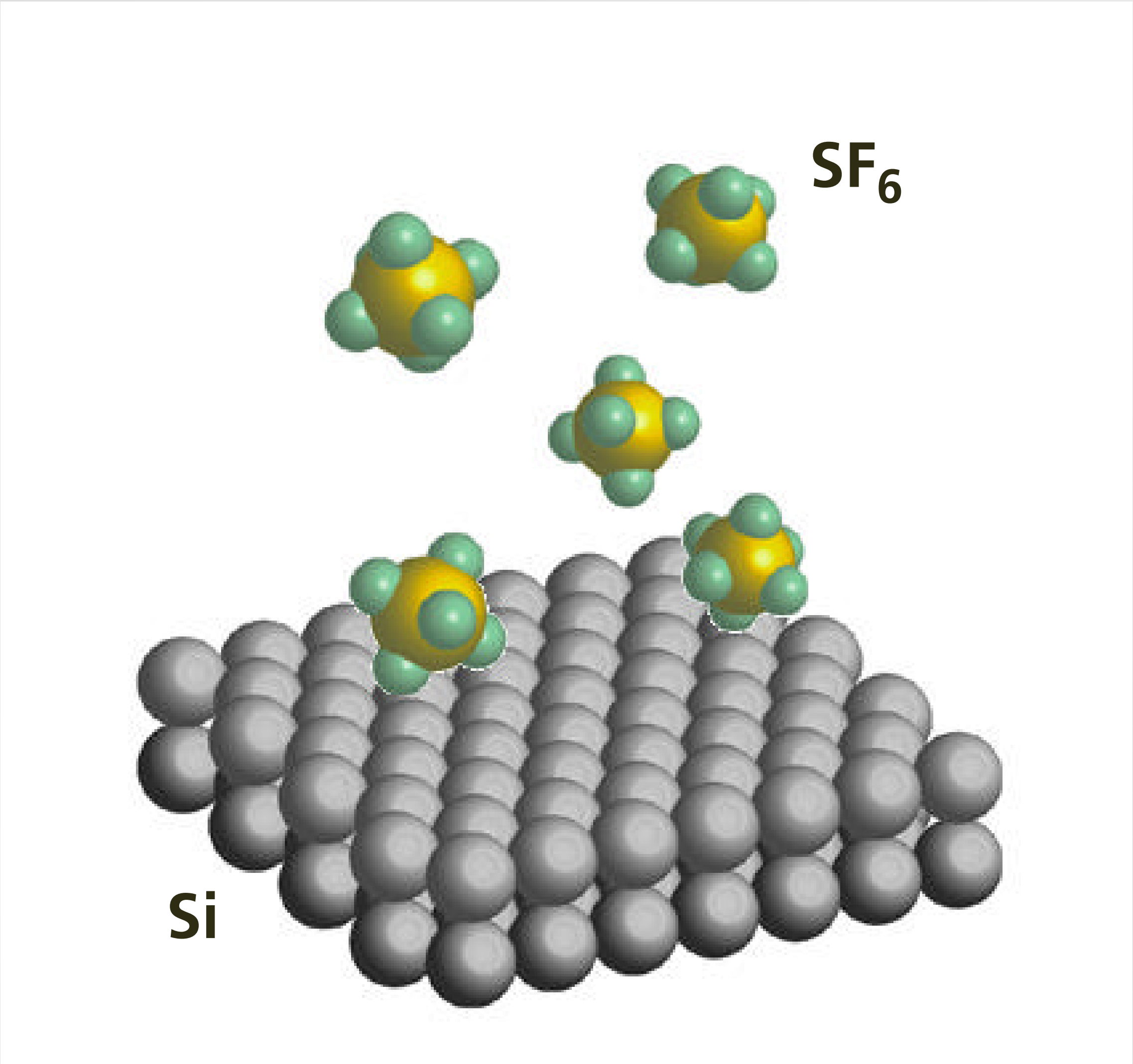


add aluminum contacts

Outline

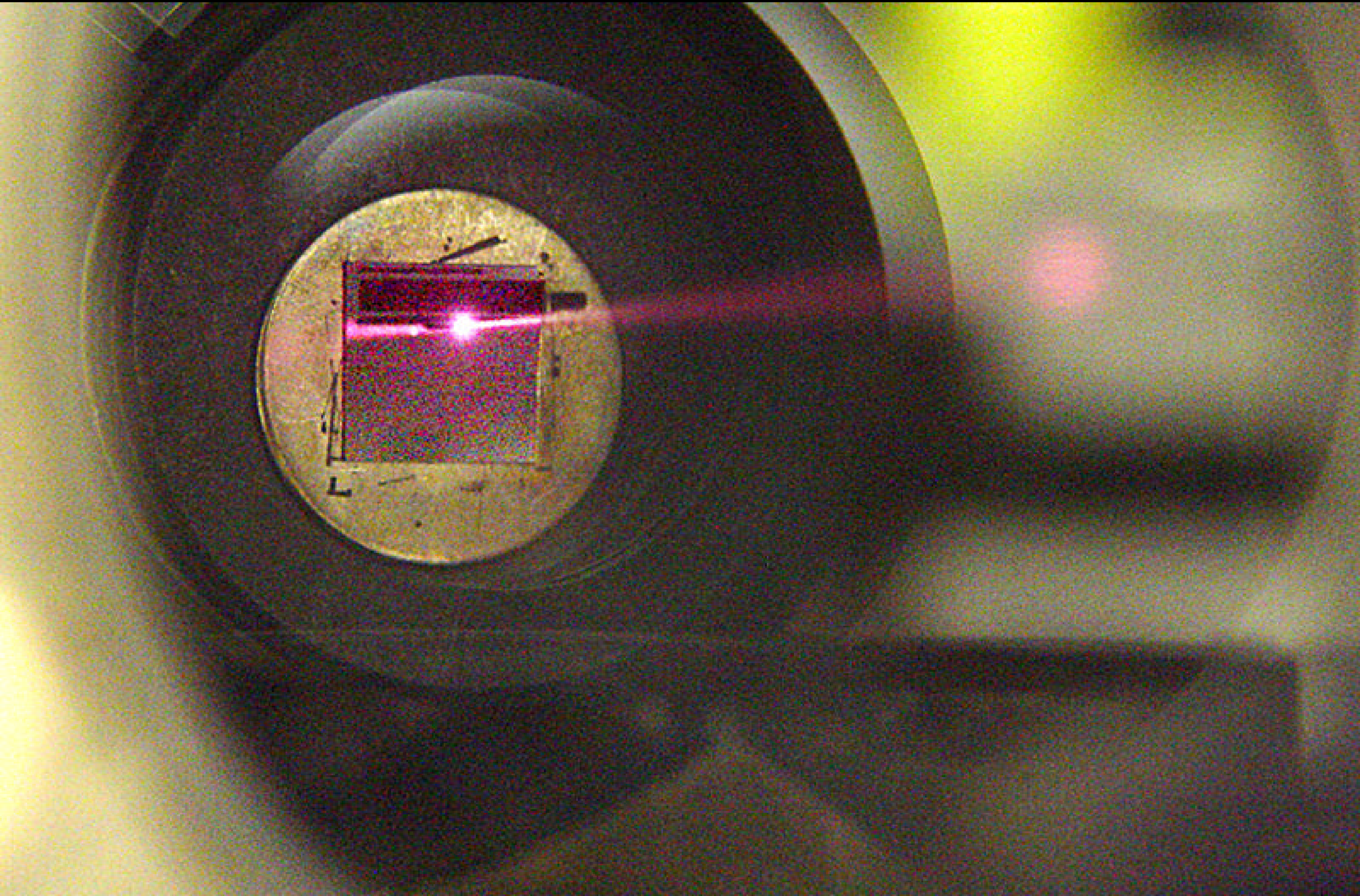
- doped semiconductors
- pn-junctions
- **black silicon**

Black silicon

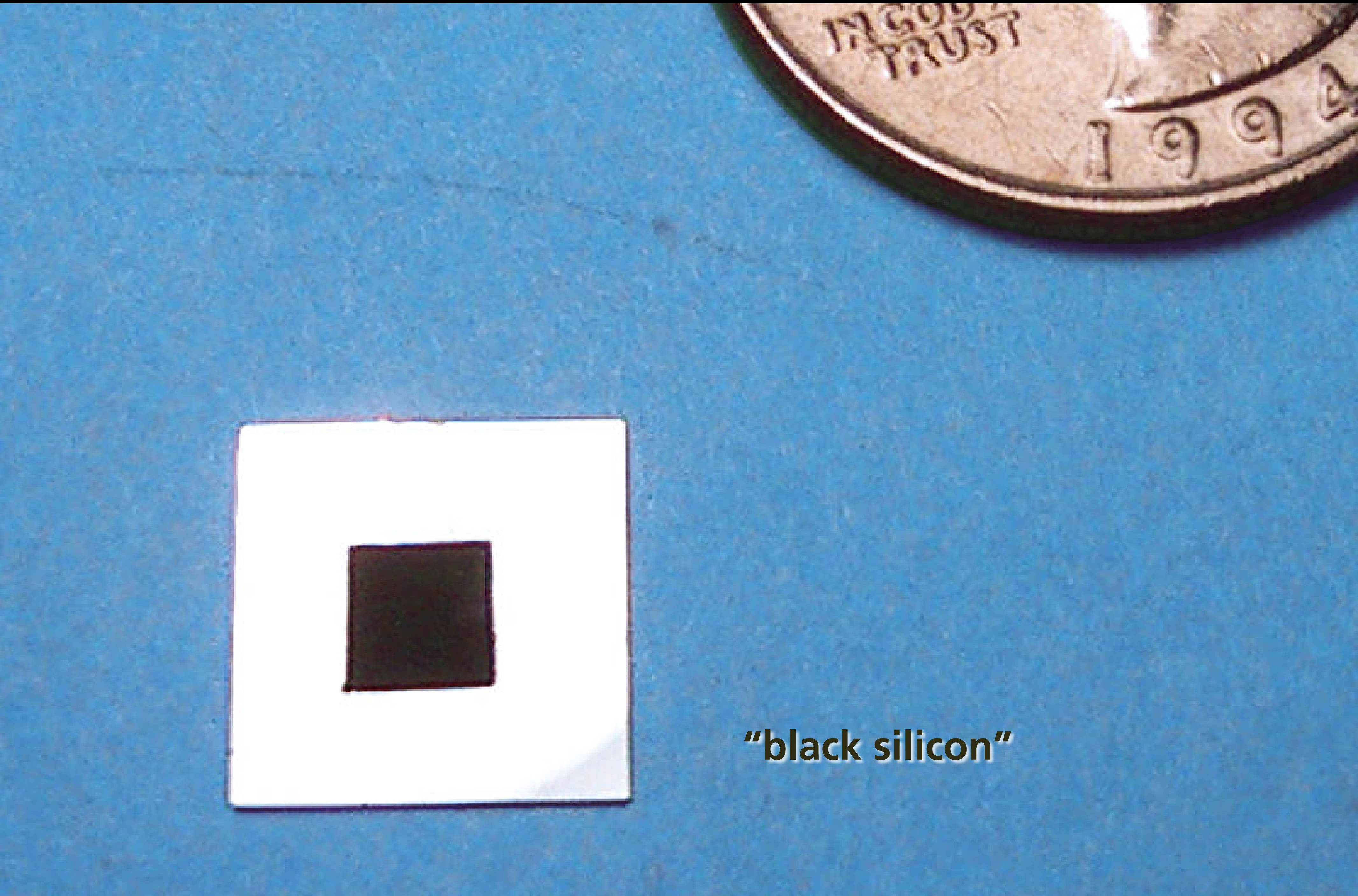


irradiate with 100-fs 10 kJ/m^2 pulses

Black silicon



Black silicon



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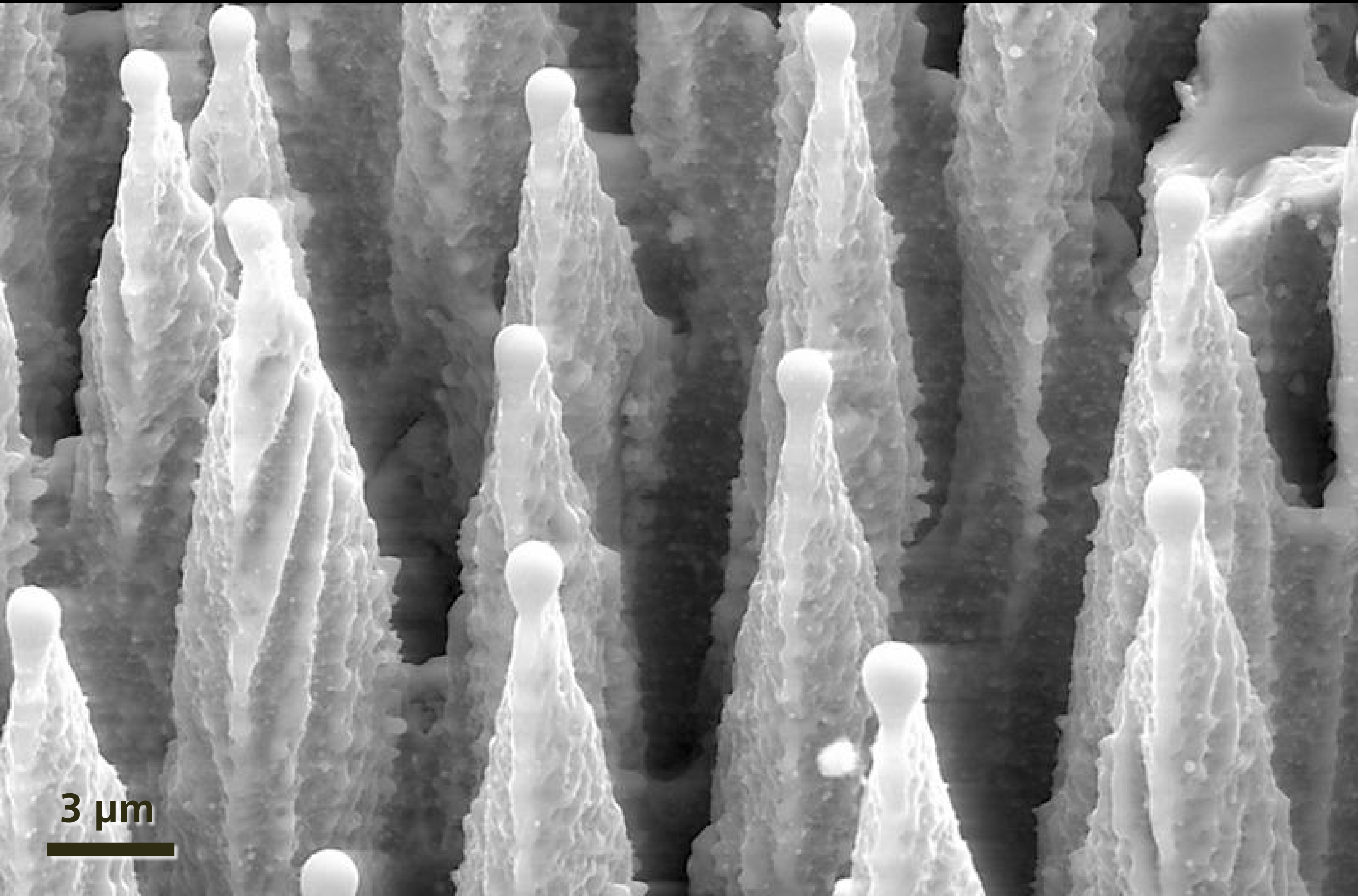

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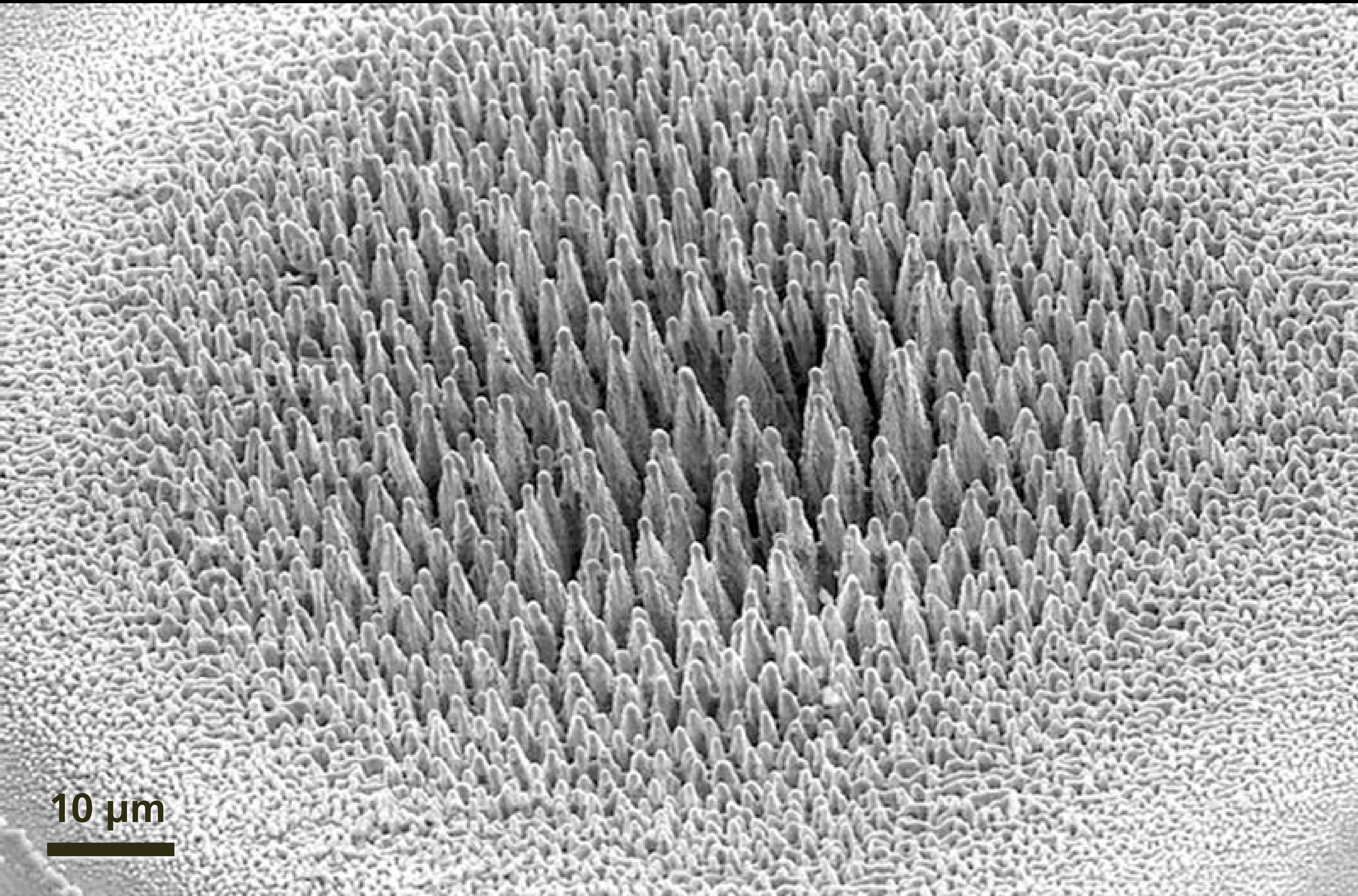

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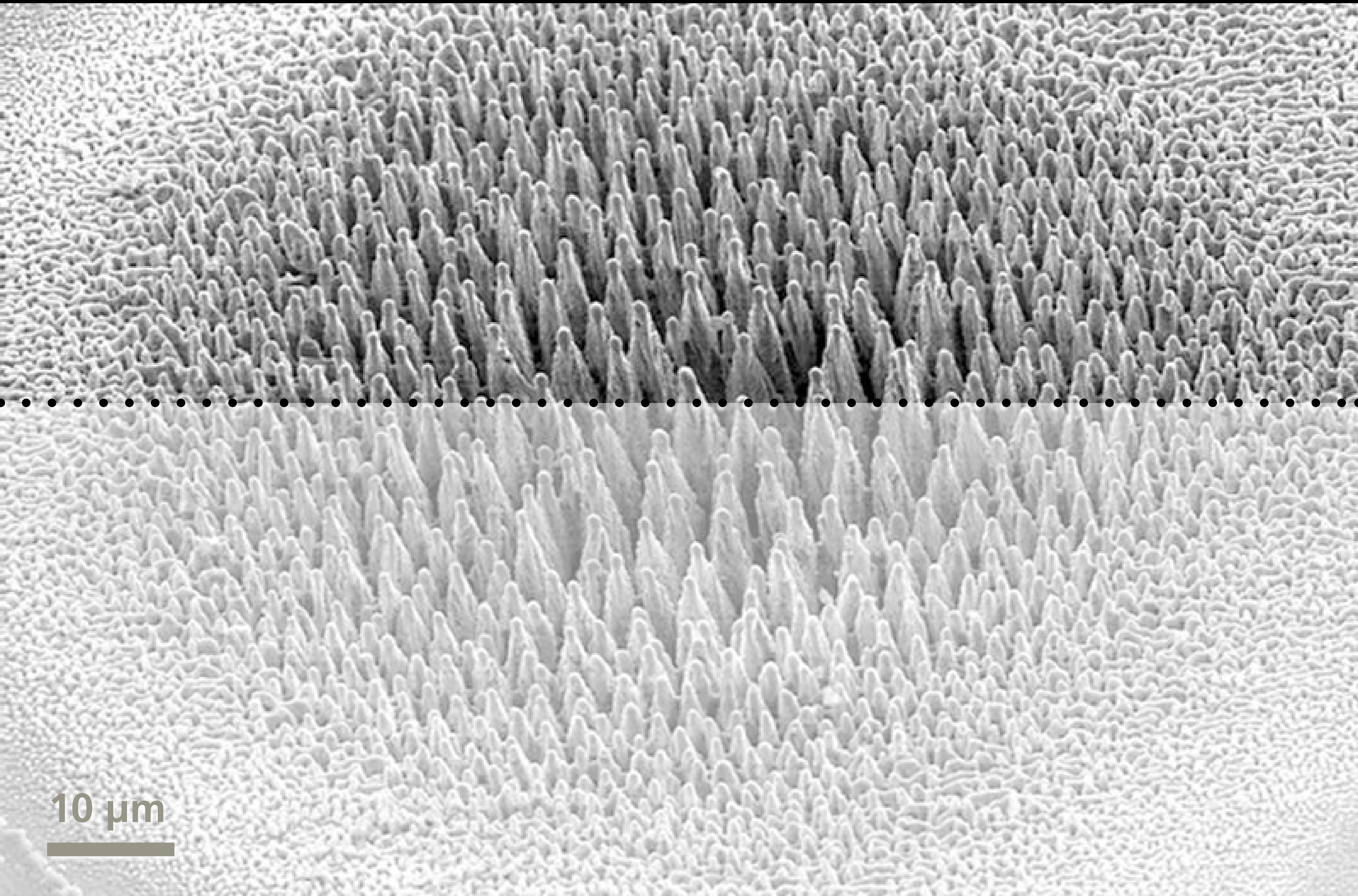

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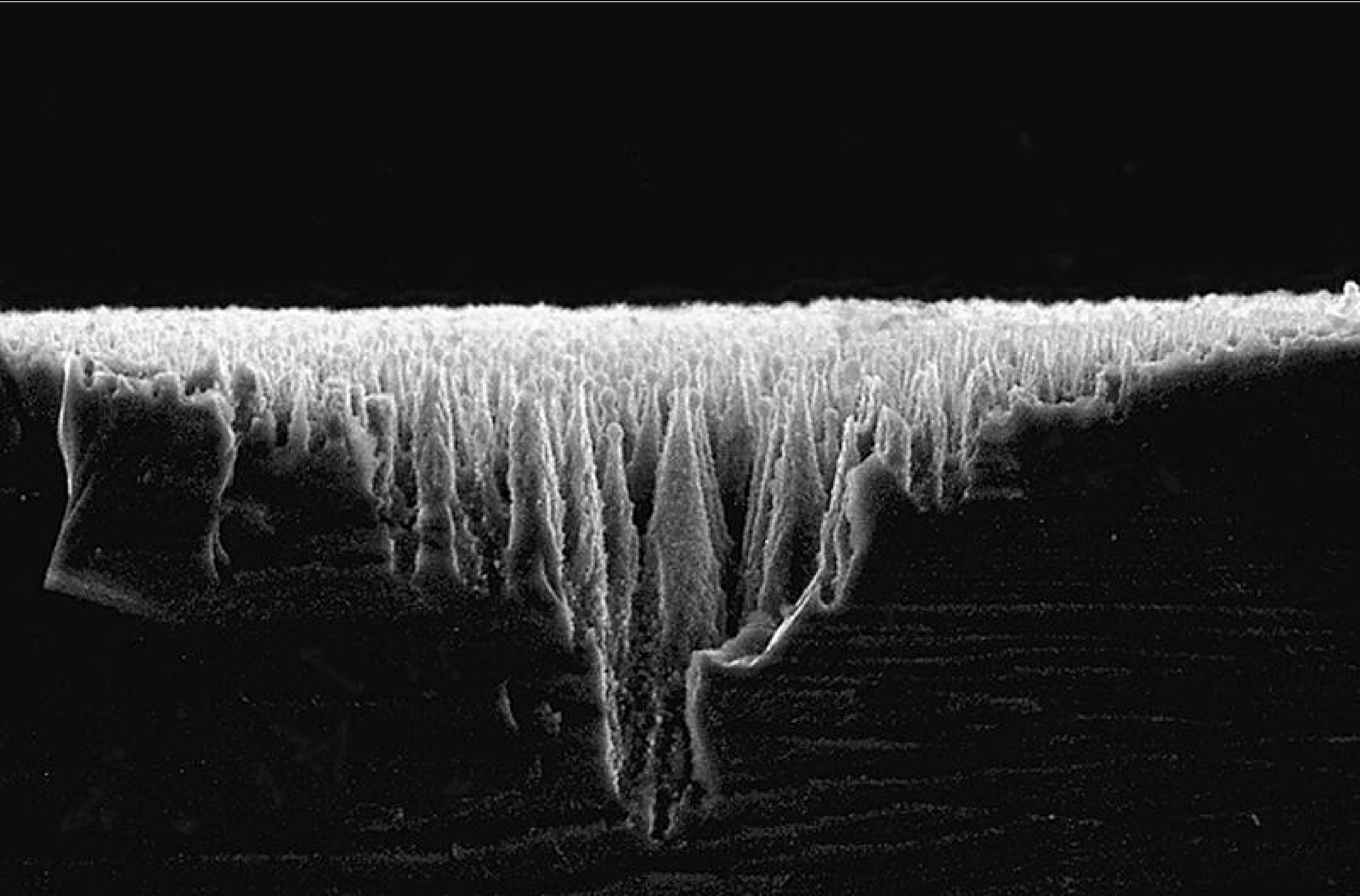

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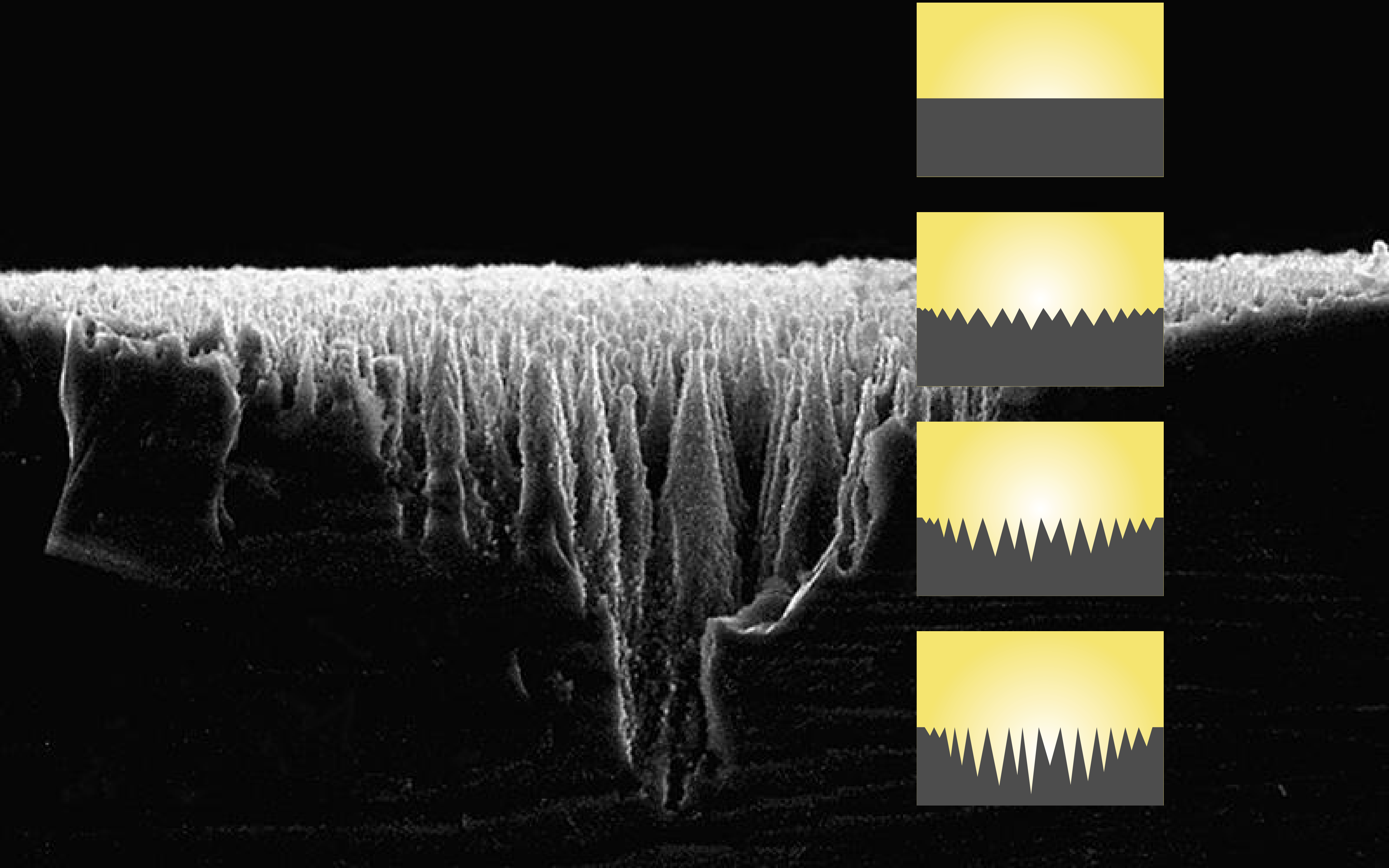
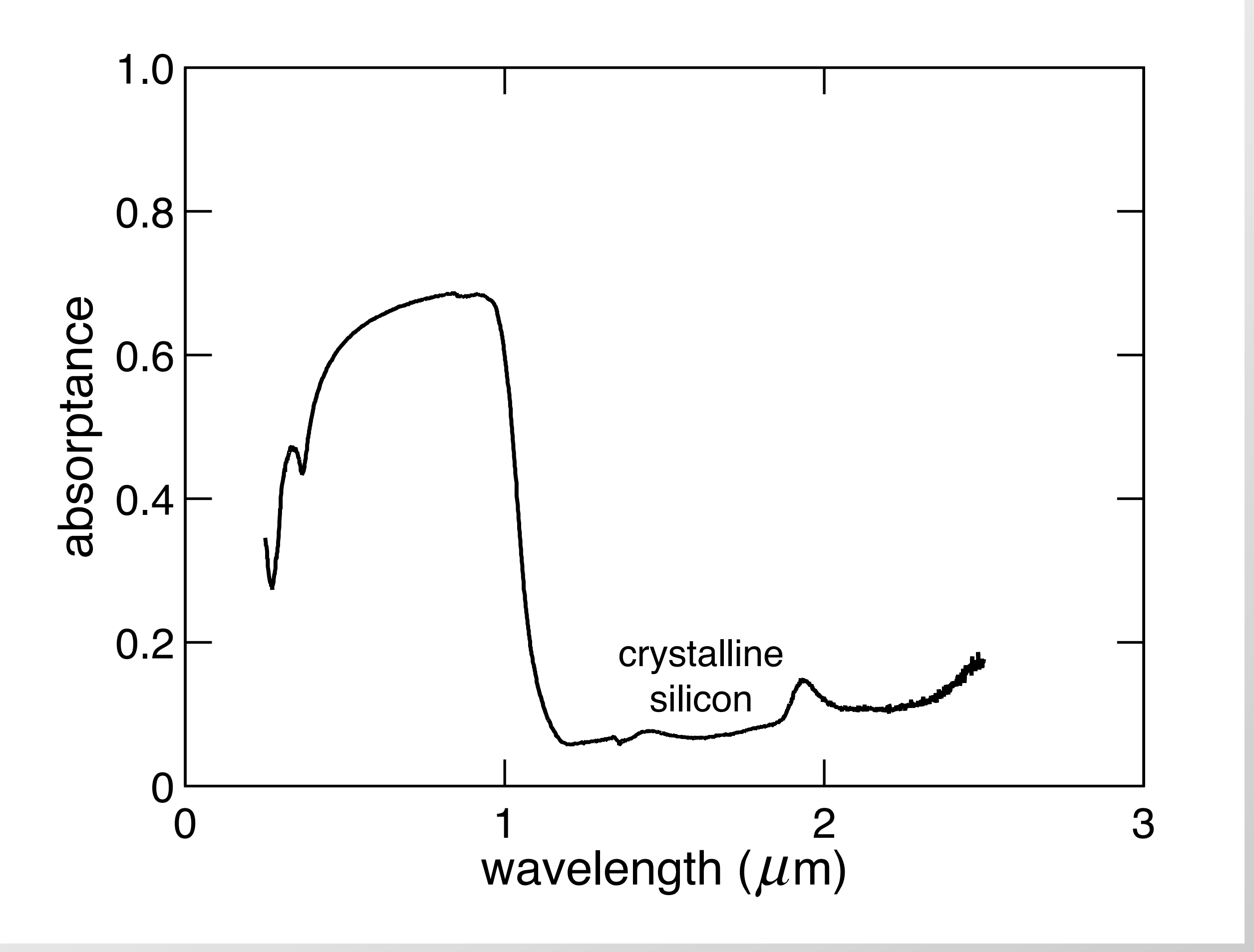


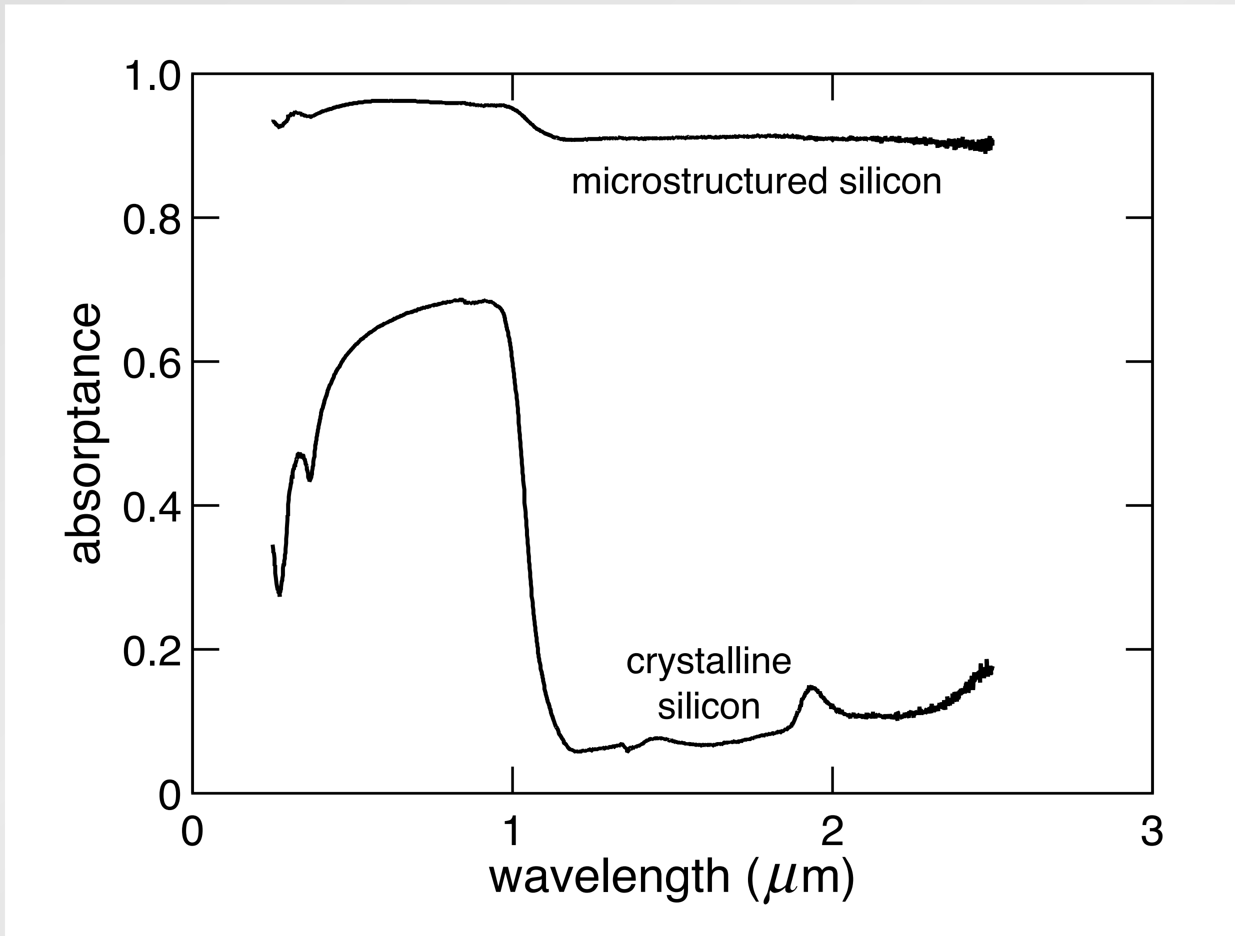
Black silicon

absorptance



Black silicon

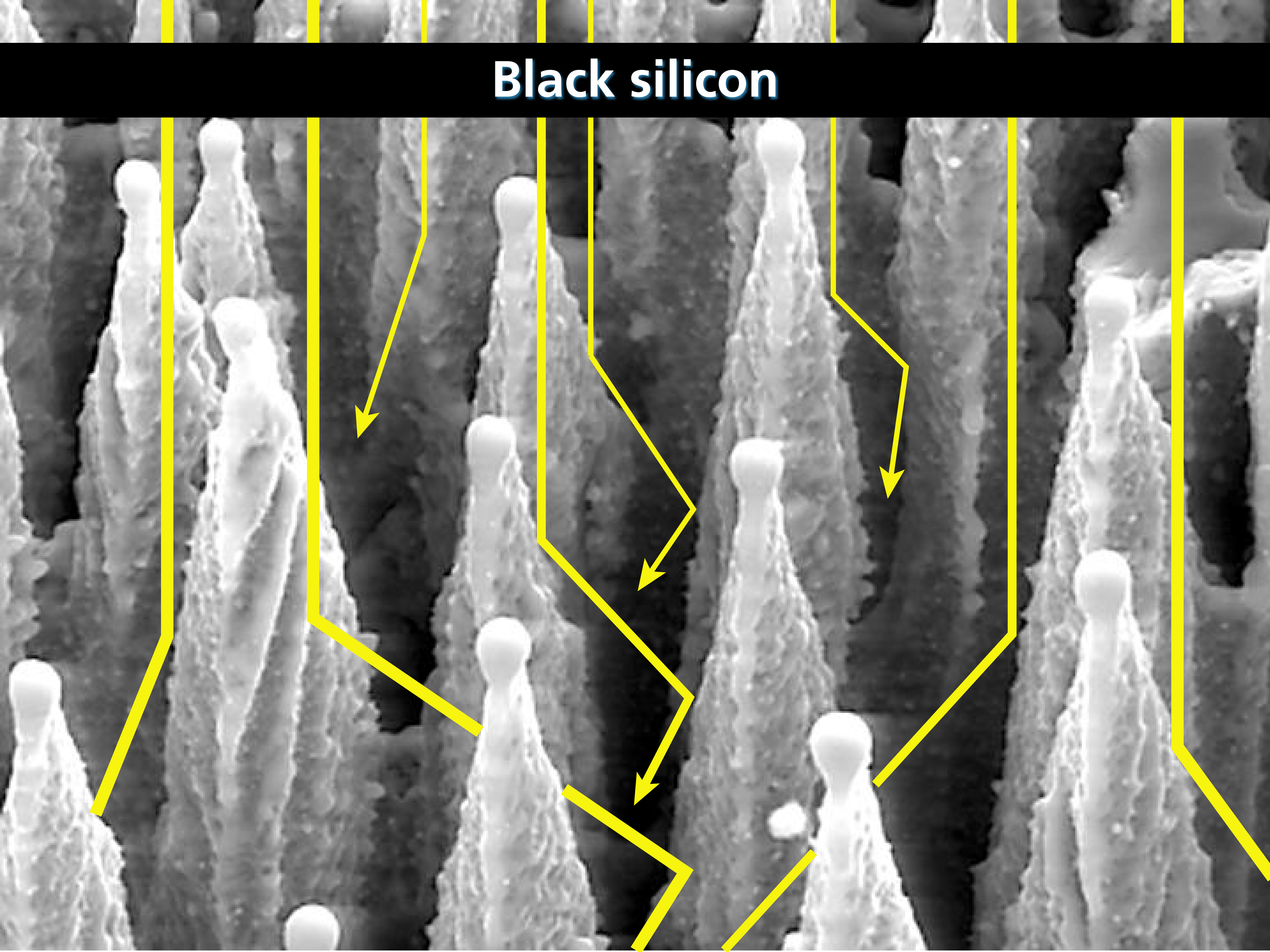
absorptance



Black silicon

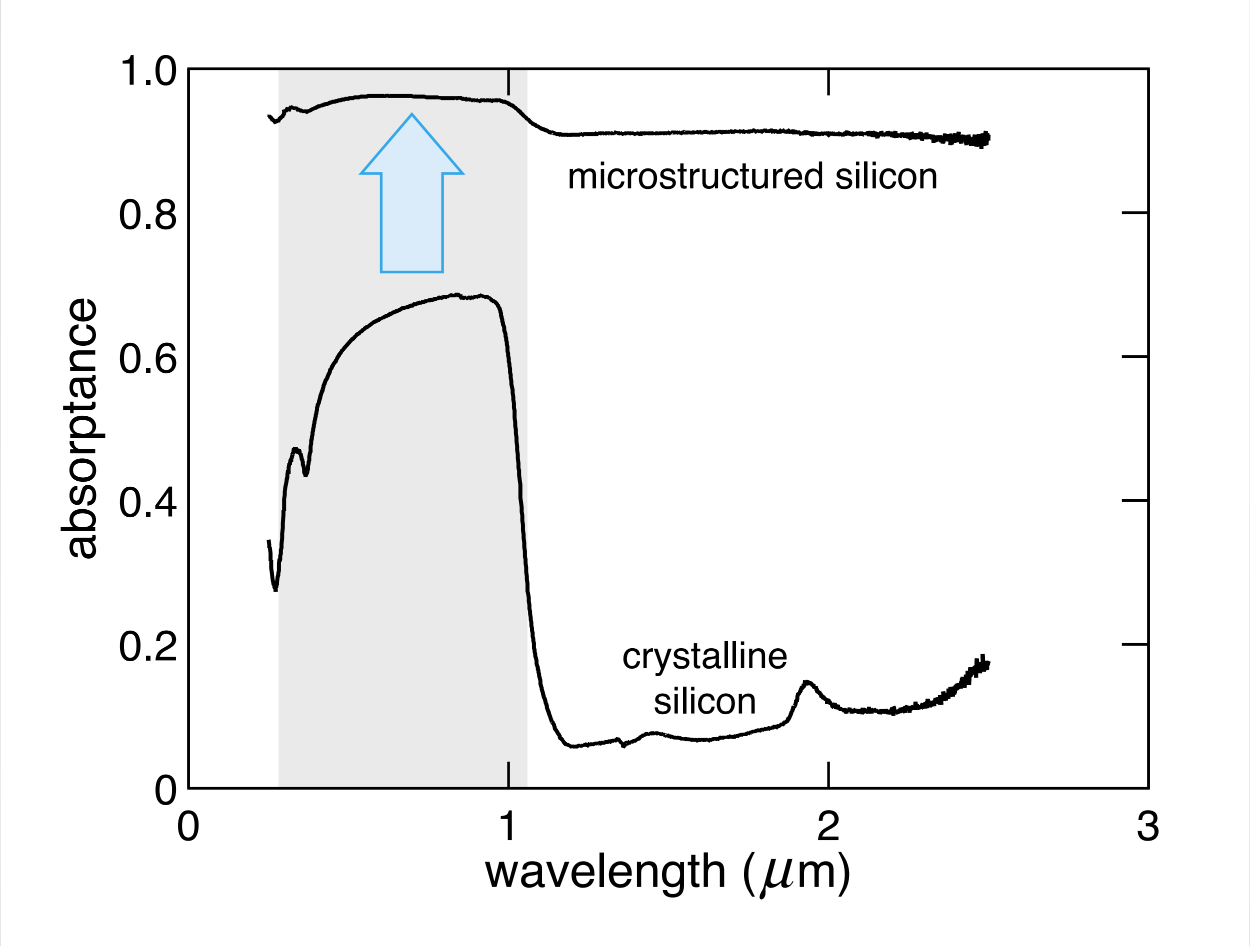
What causes the near-unity absorptance?

Black silicon



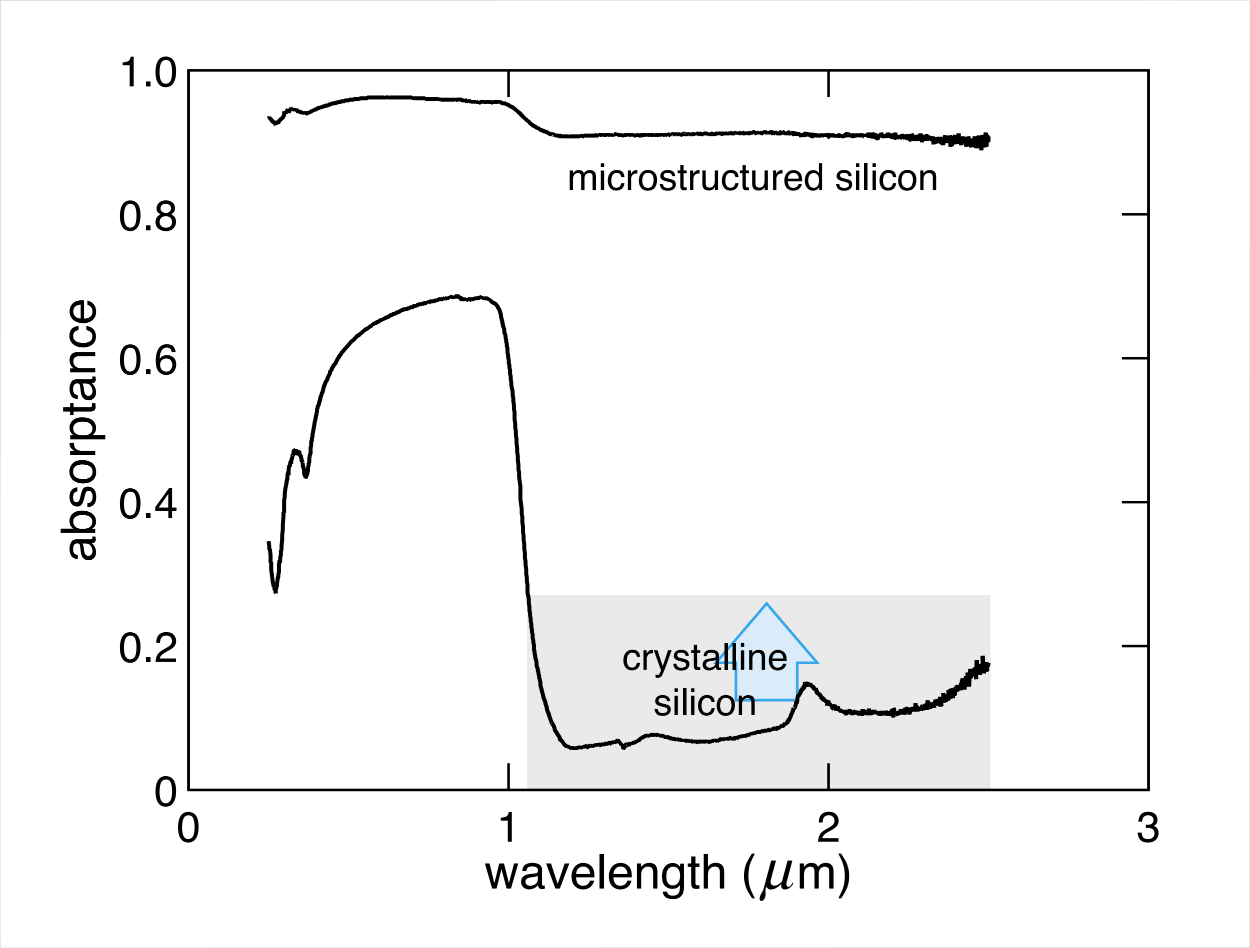
Black silicon

multiple reflections enhance absorption



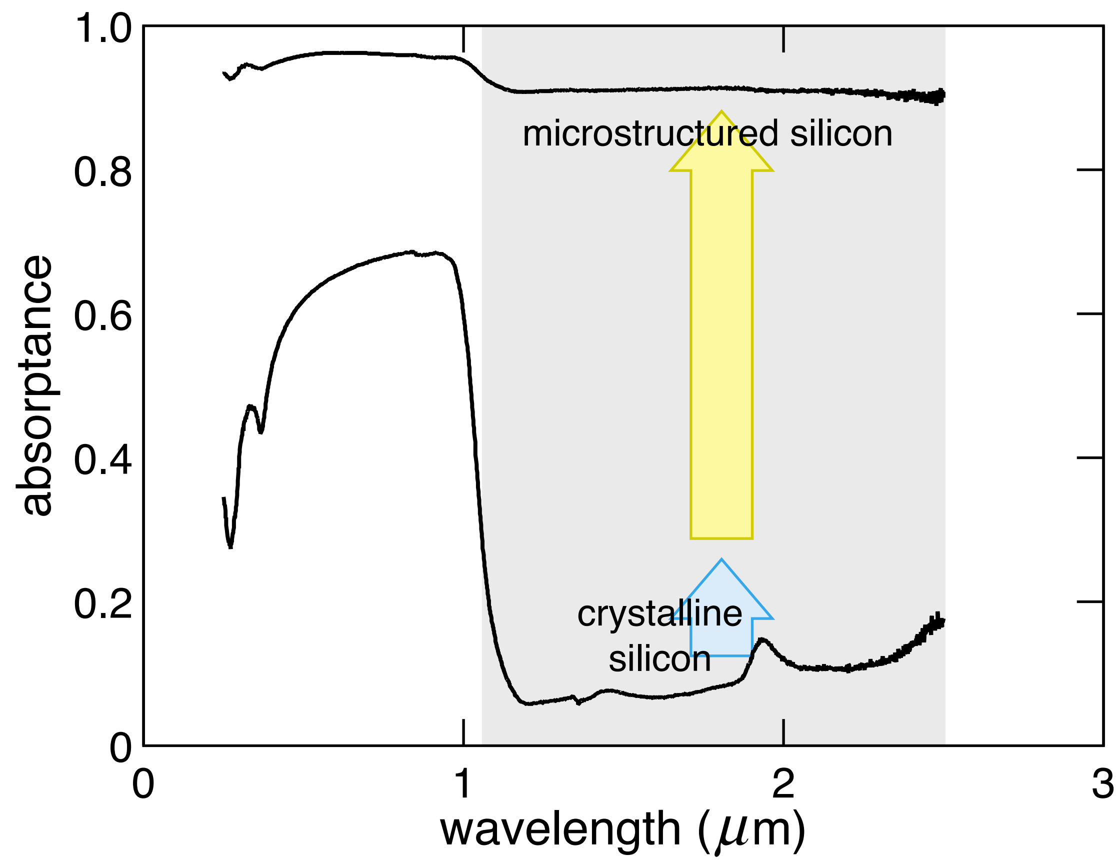
Black silicon

multiple reflections enhance absorption

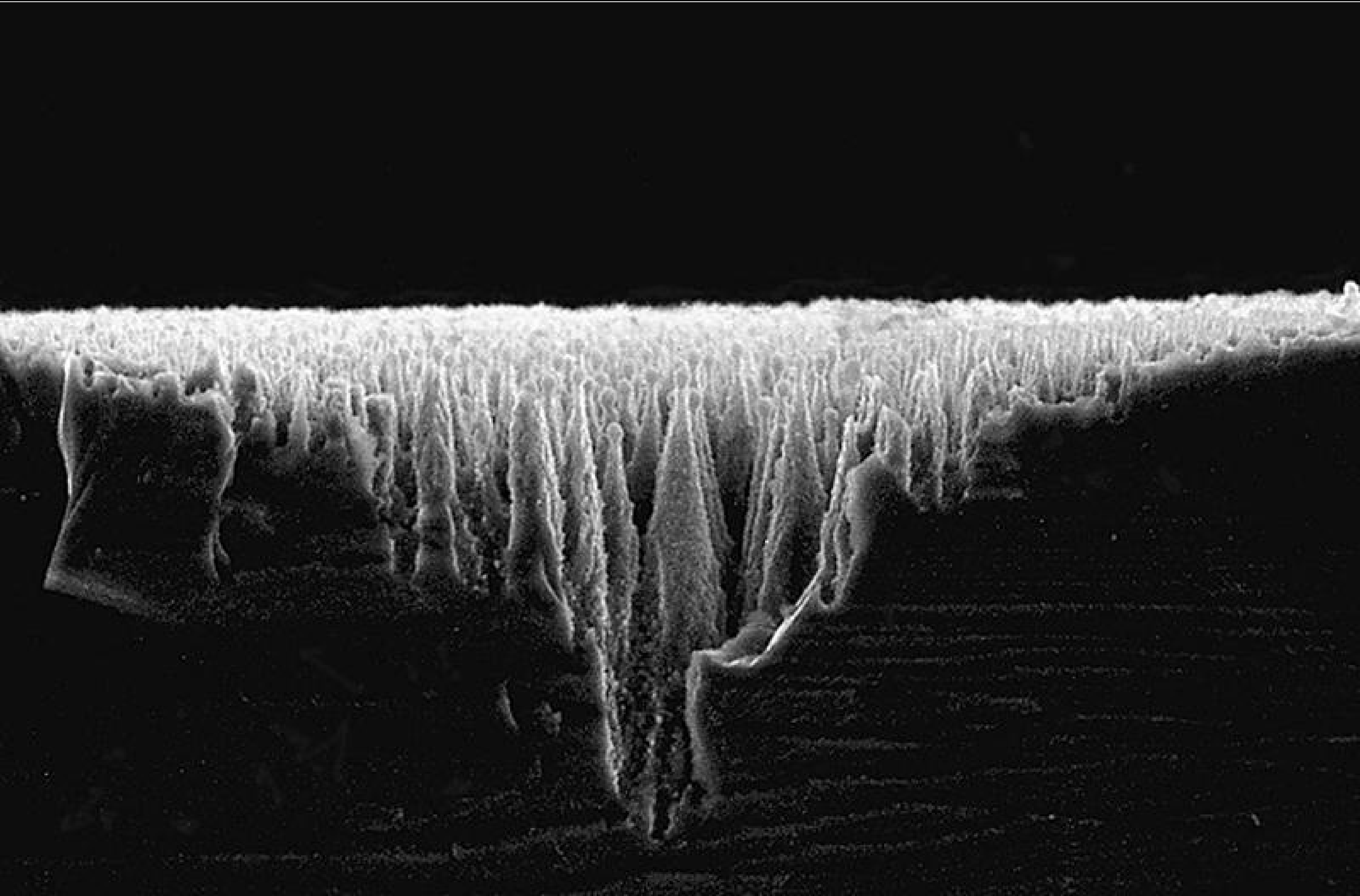


Black silicon

heavy sulfur doping causes infrared absorption



Black silicon



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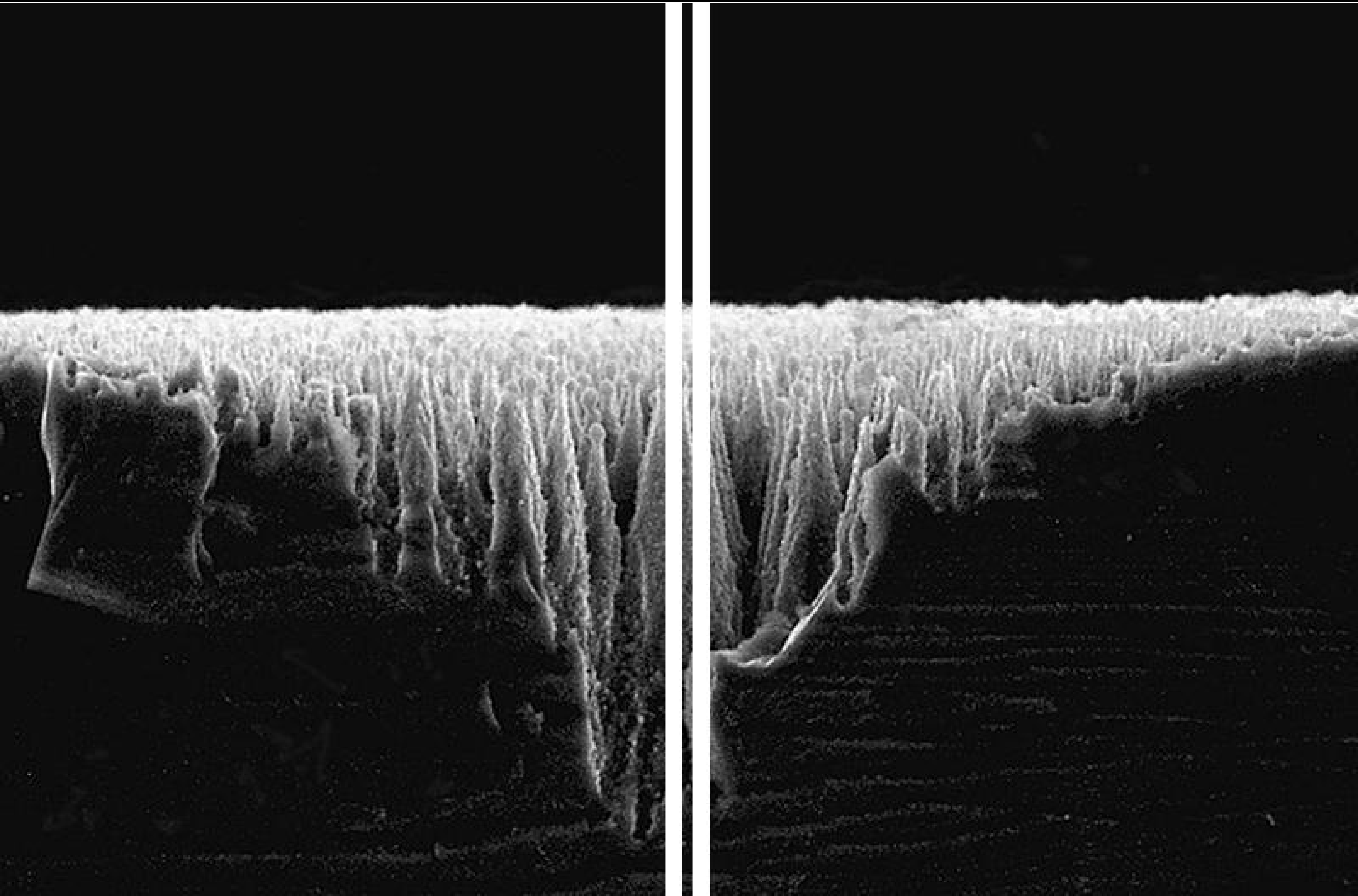
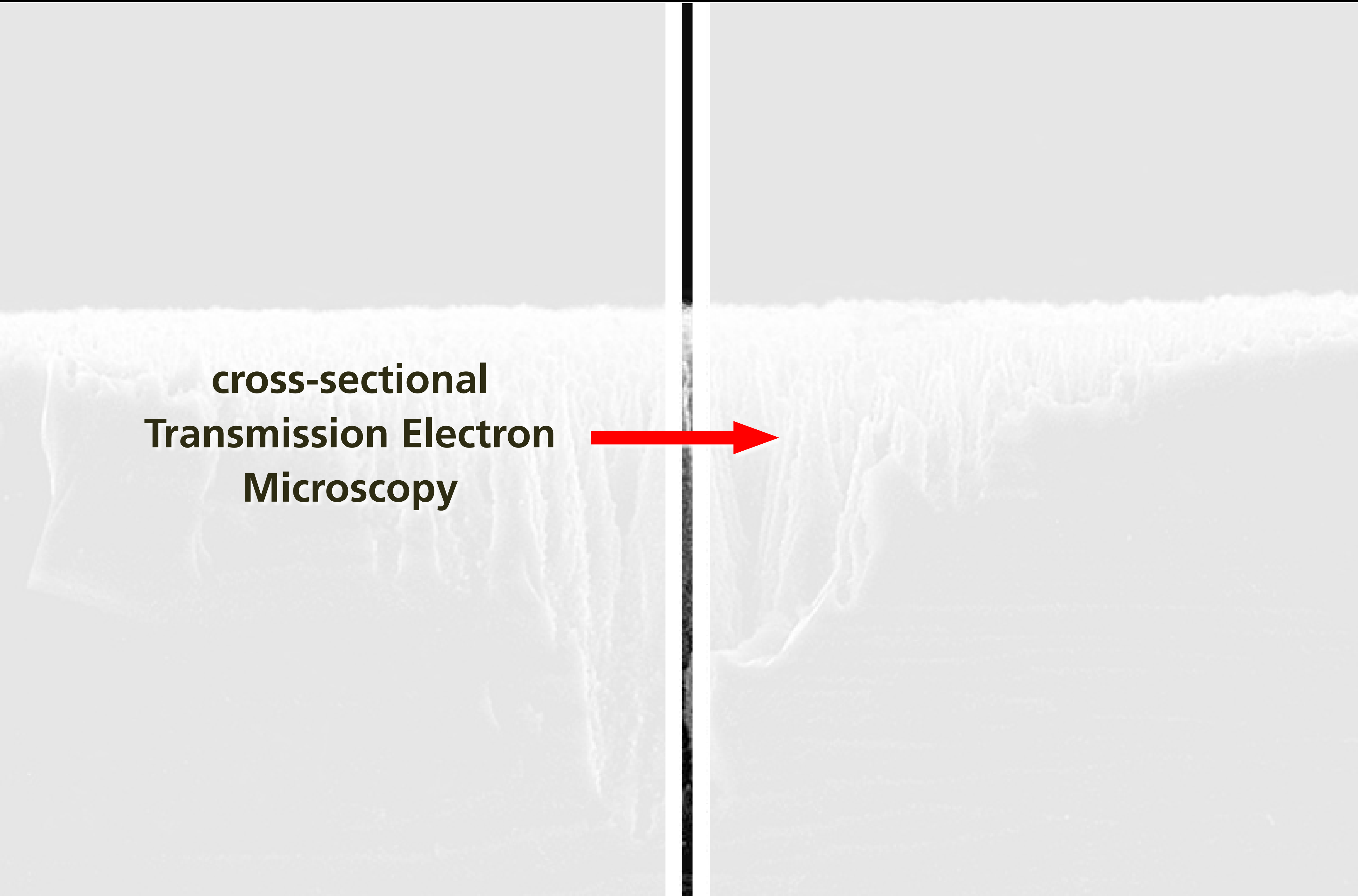


Black silicon



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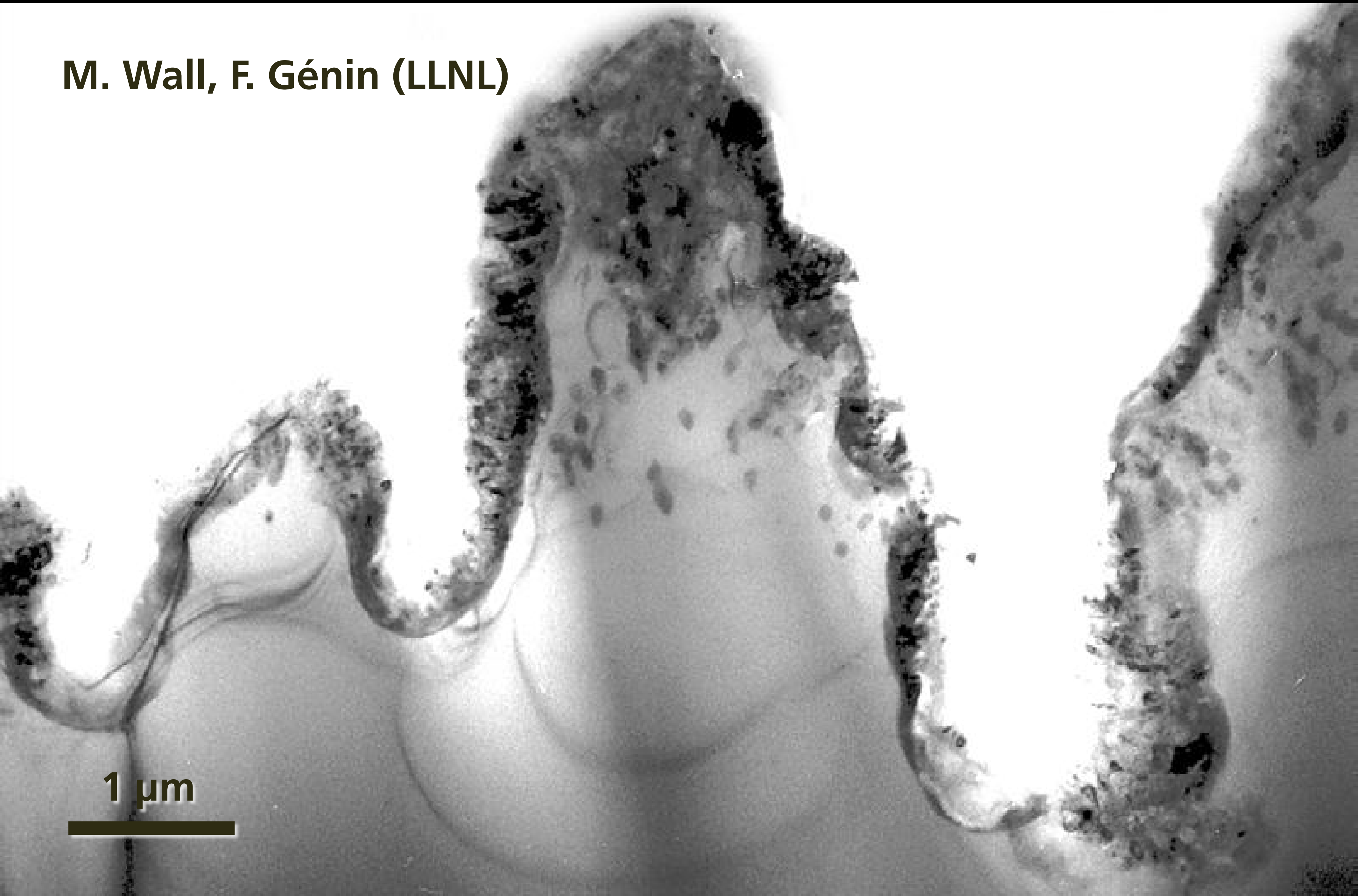

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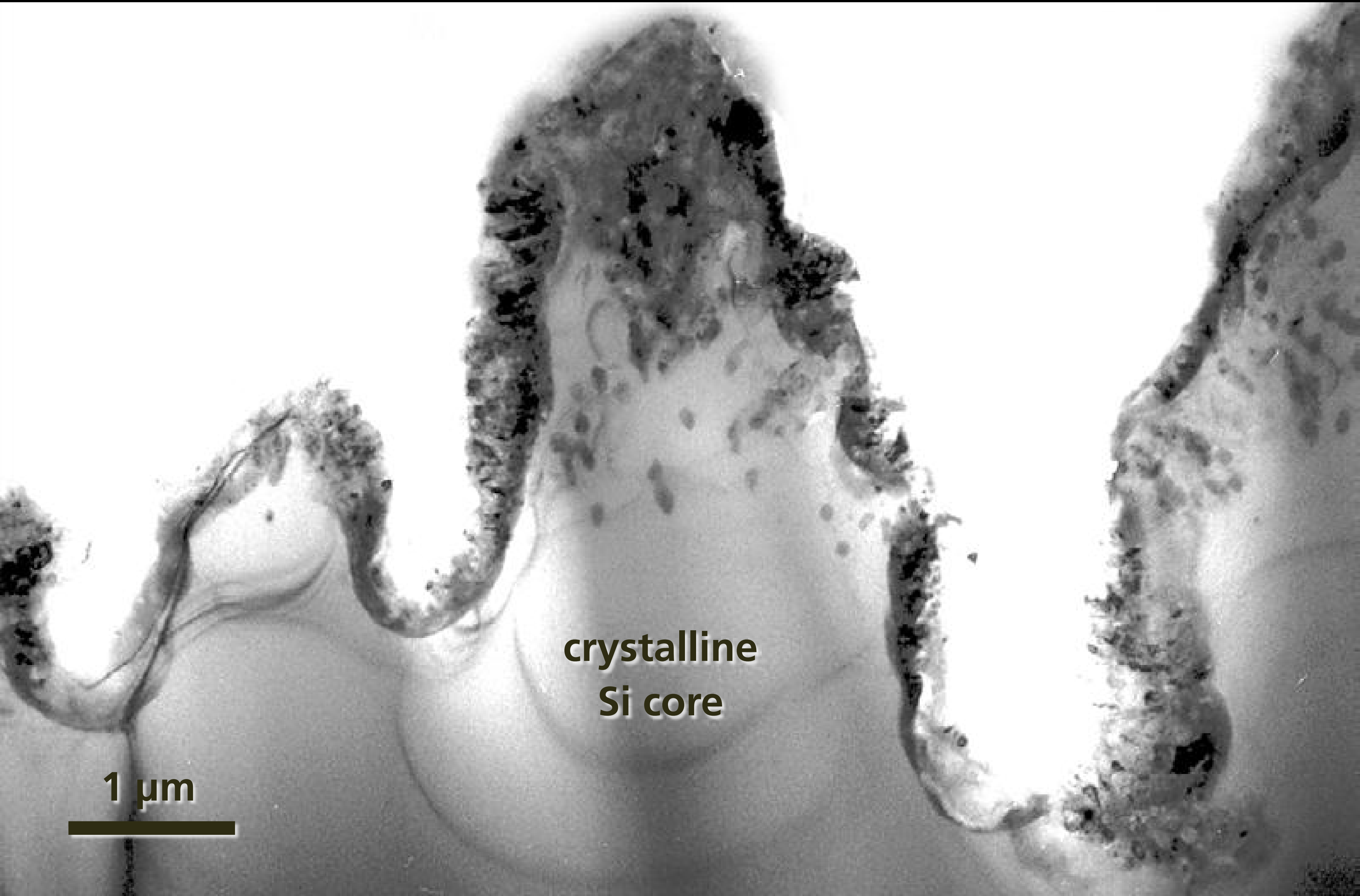
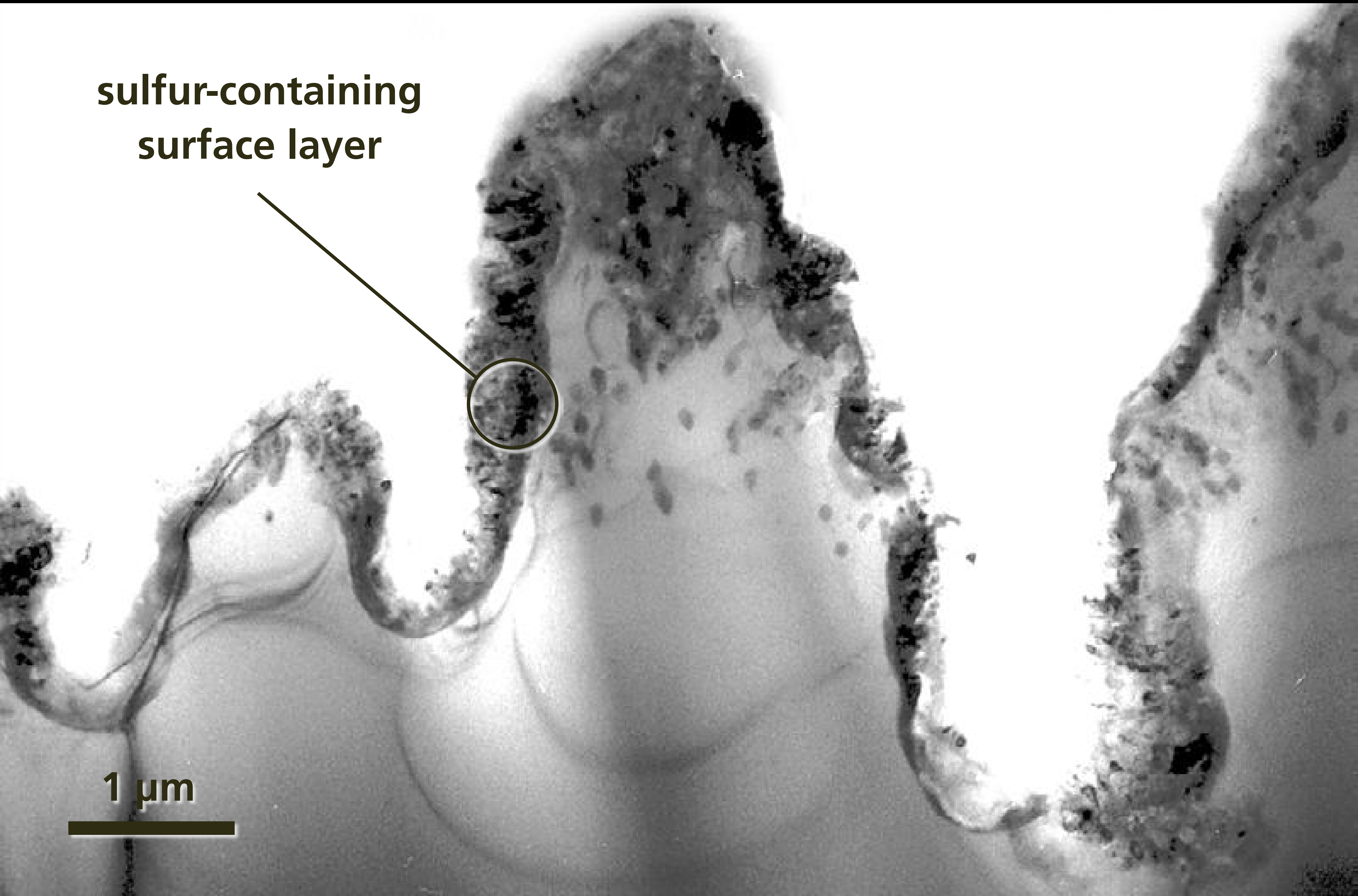
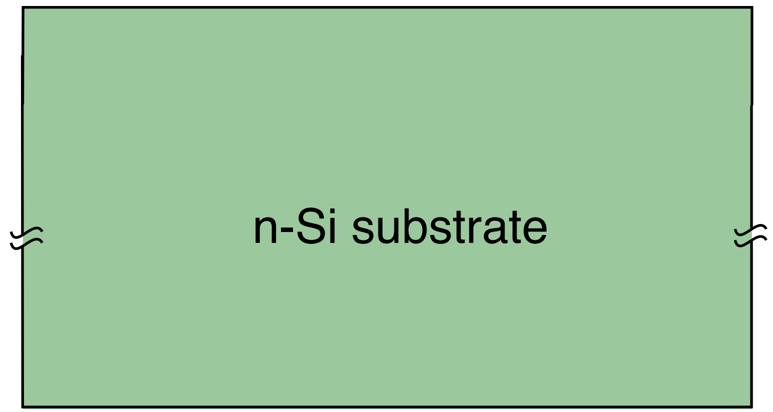


Black silicon



Black silicon

black silicon/n-type silicon junction



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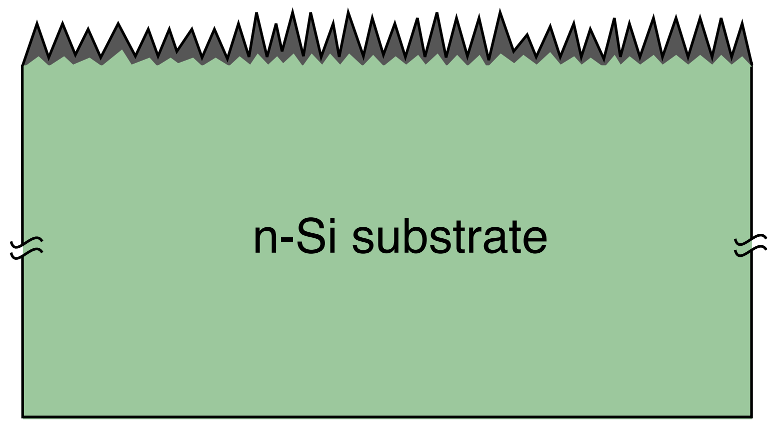

Black silicon

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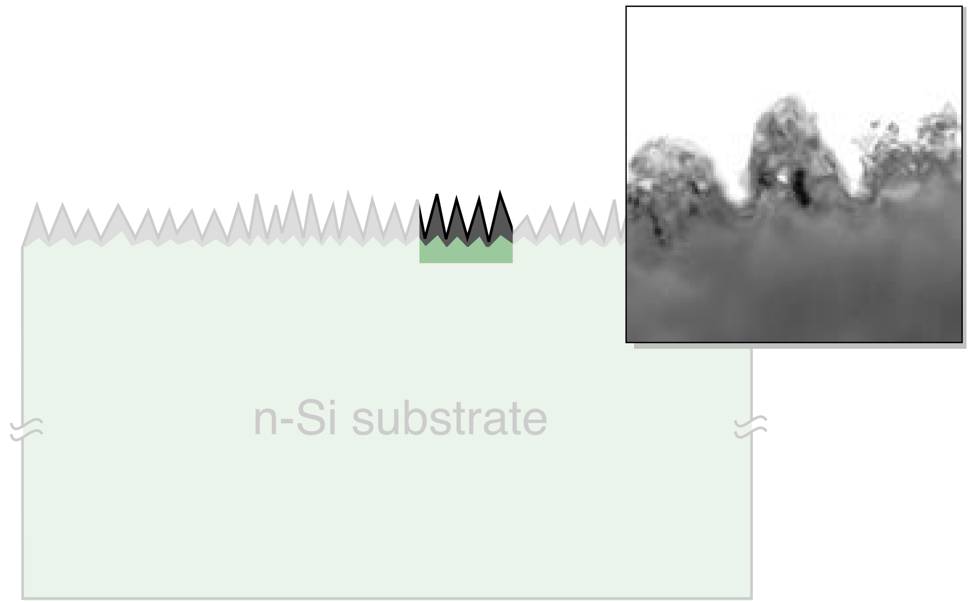

Black silicon

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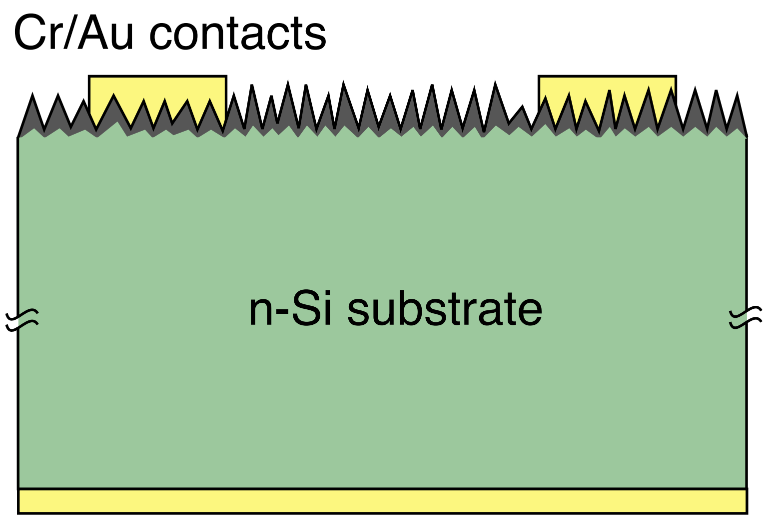
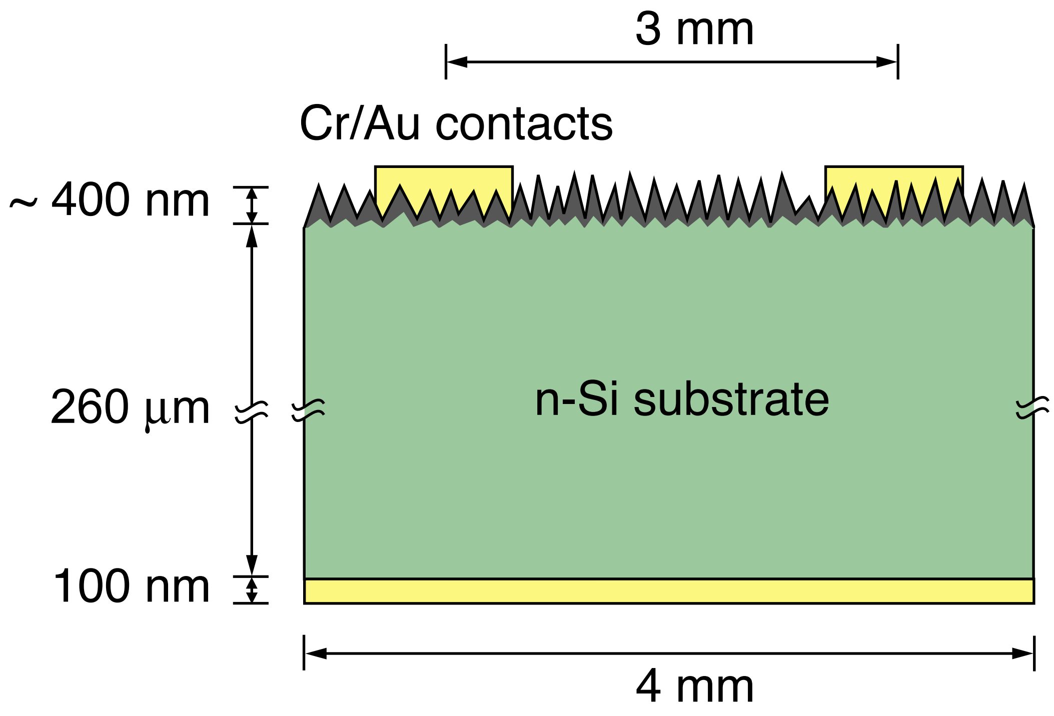


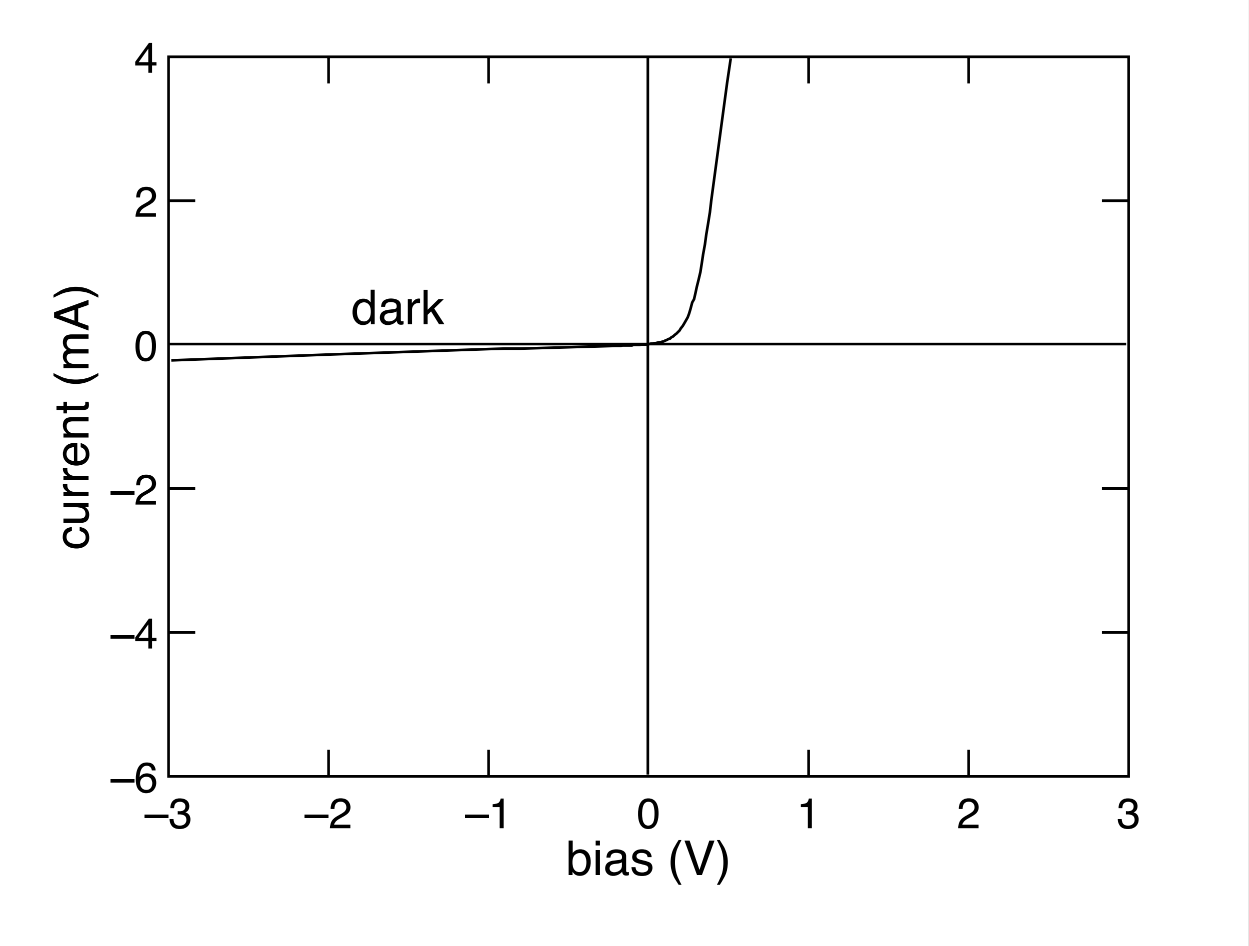
Black silicon

black silicon/n-type silicon junction



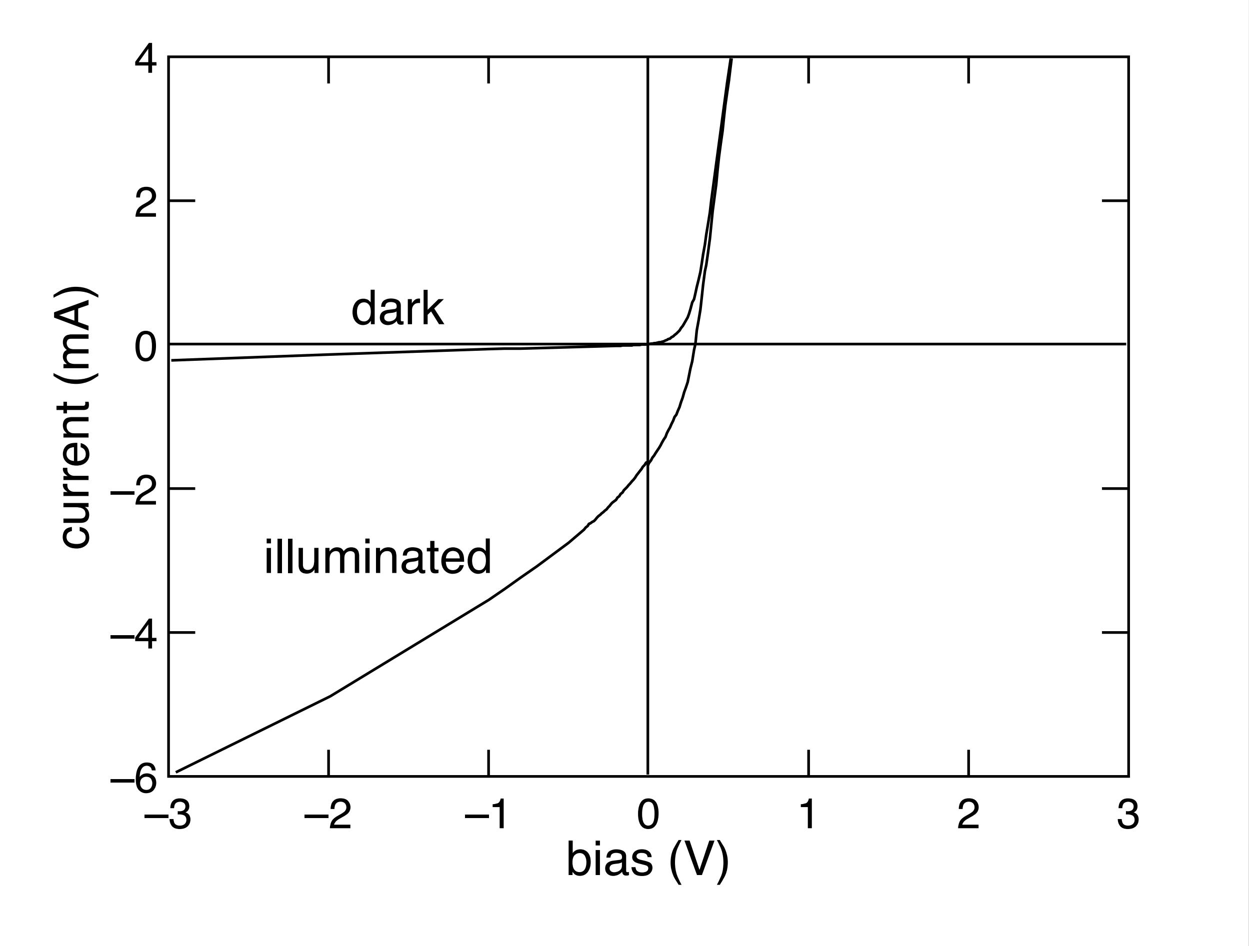
Black silicon

IV characteristics



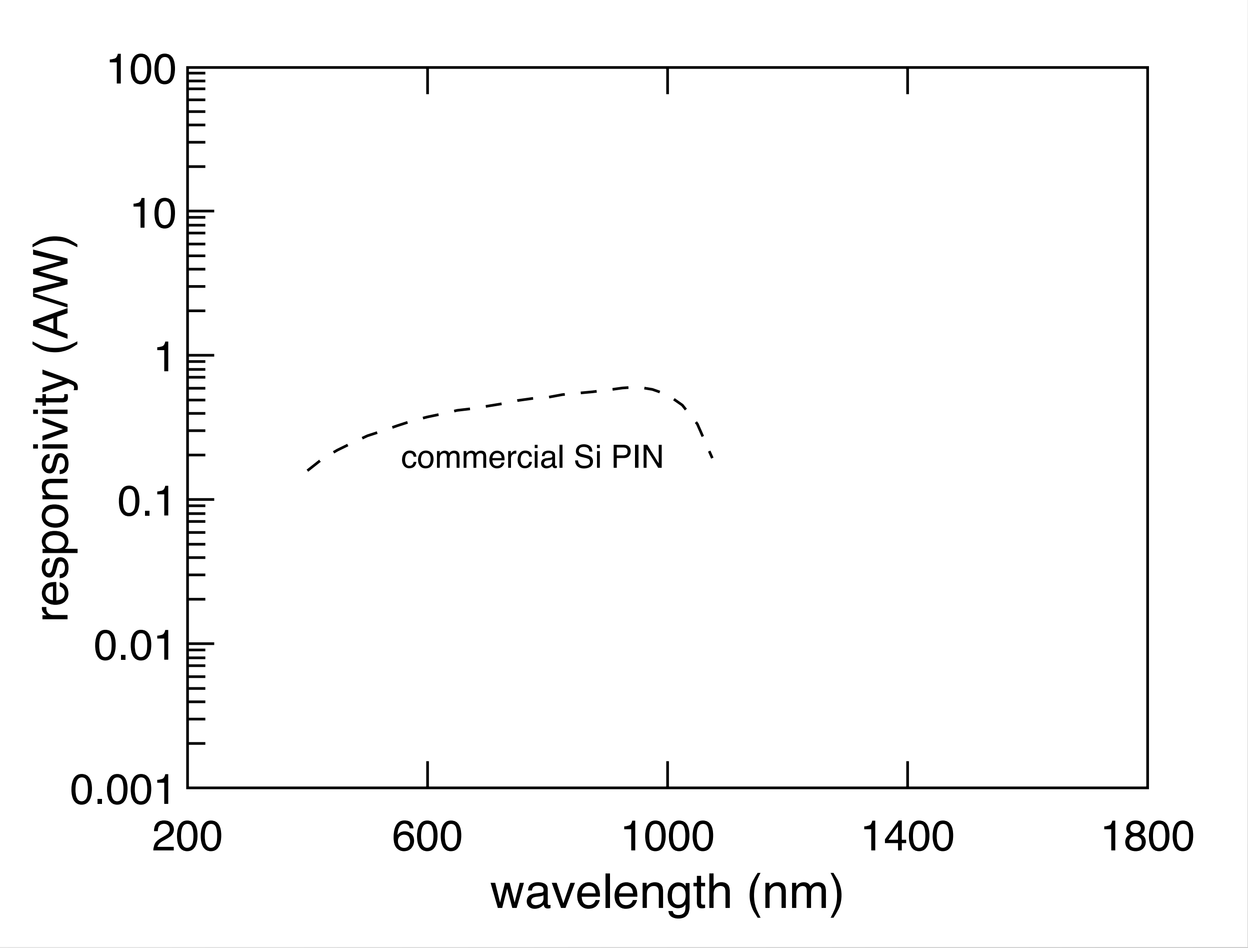
Black silicon

IV characteristics



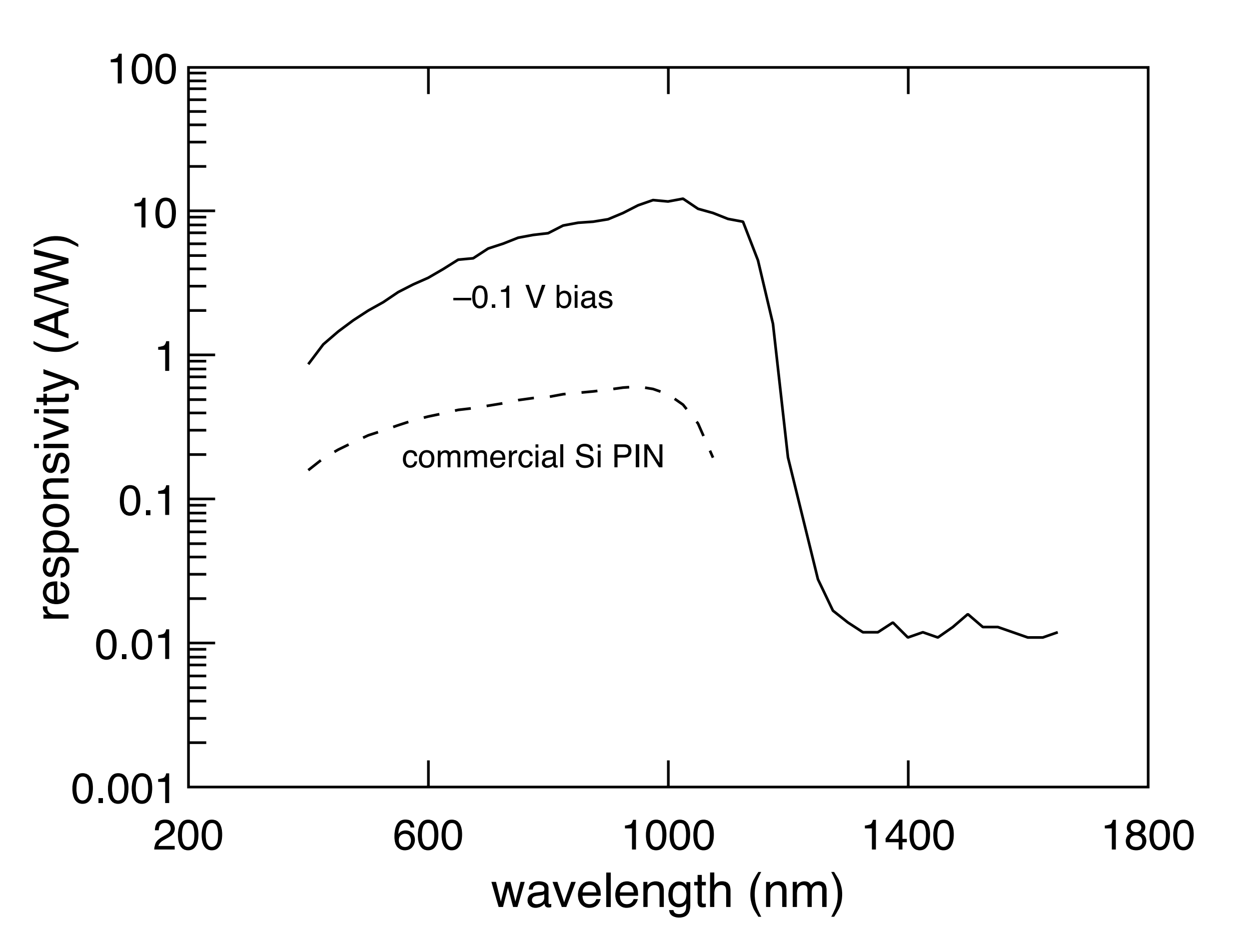
Black silicon

responsivity



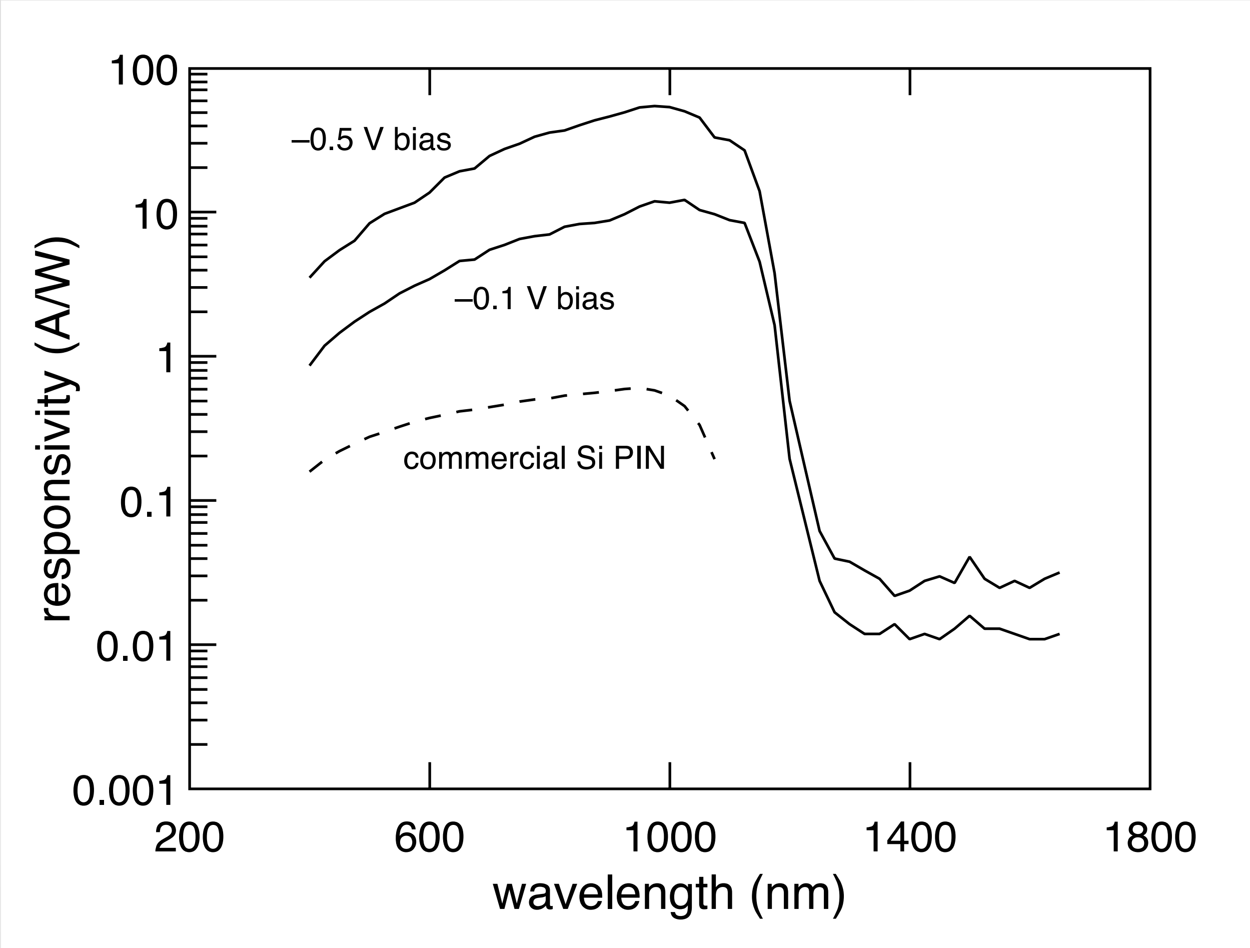
Black silicon

responsivity



Black silicon

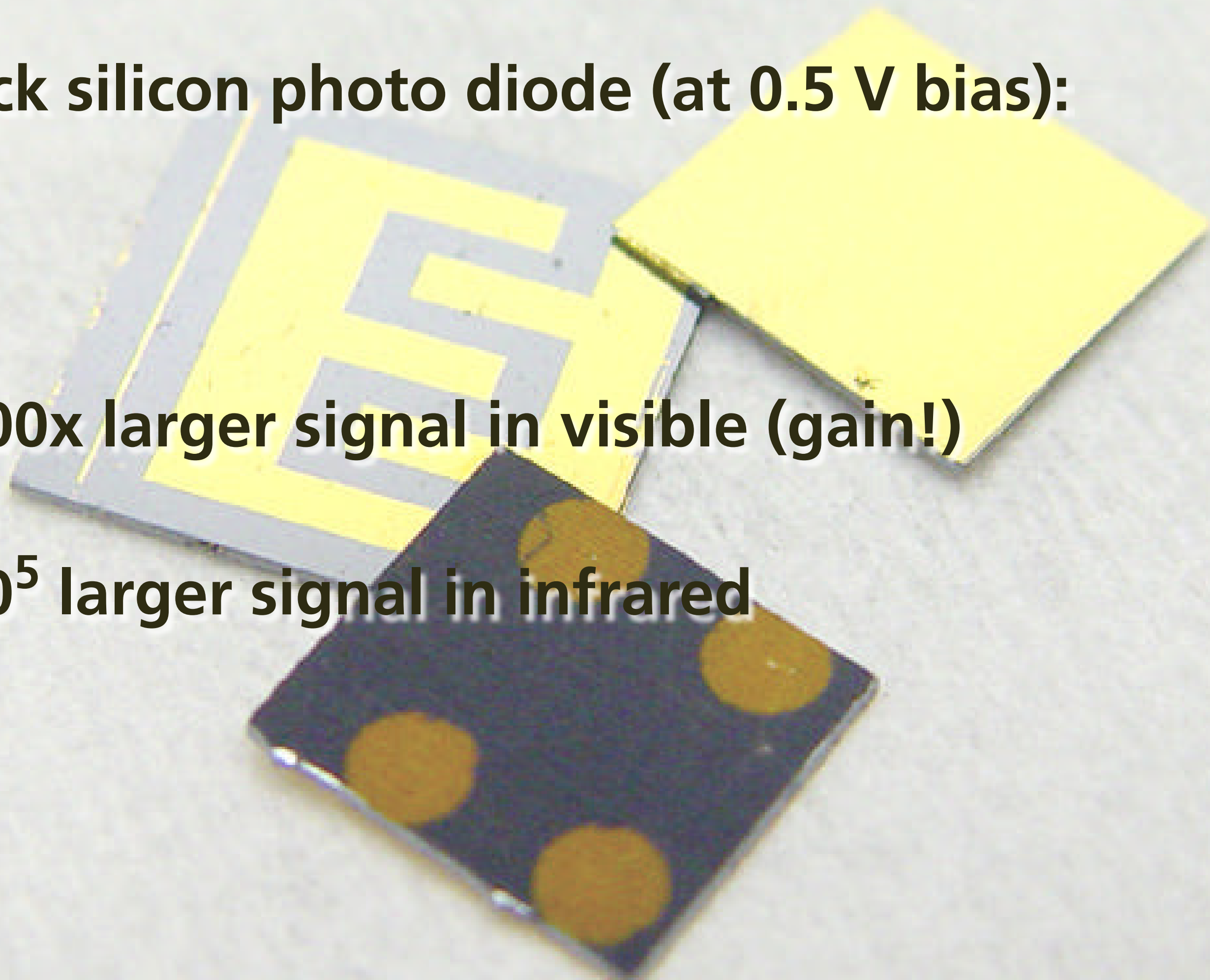
responsivity



Black silicon

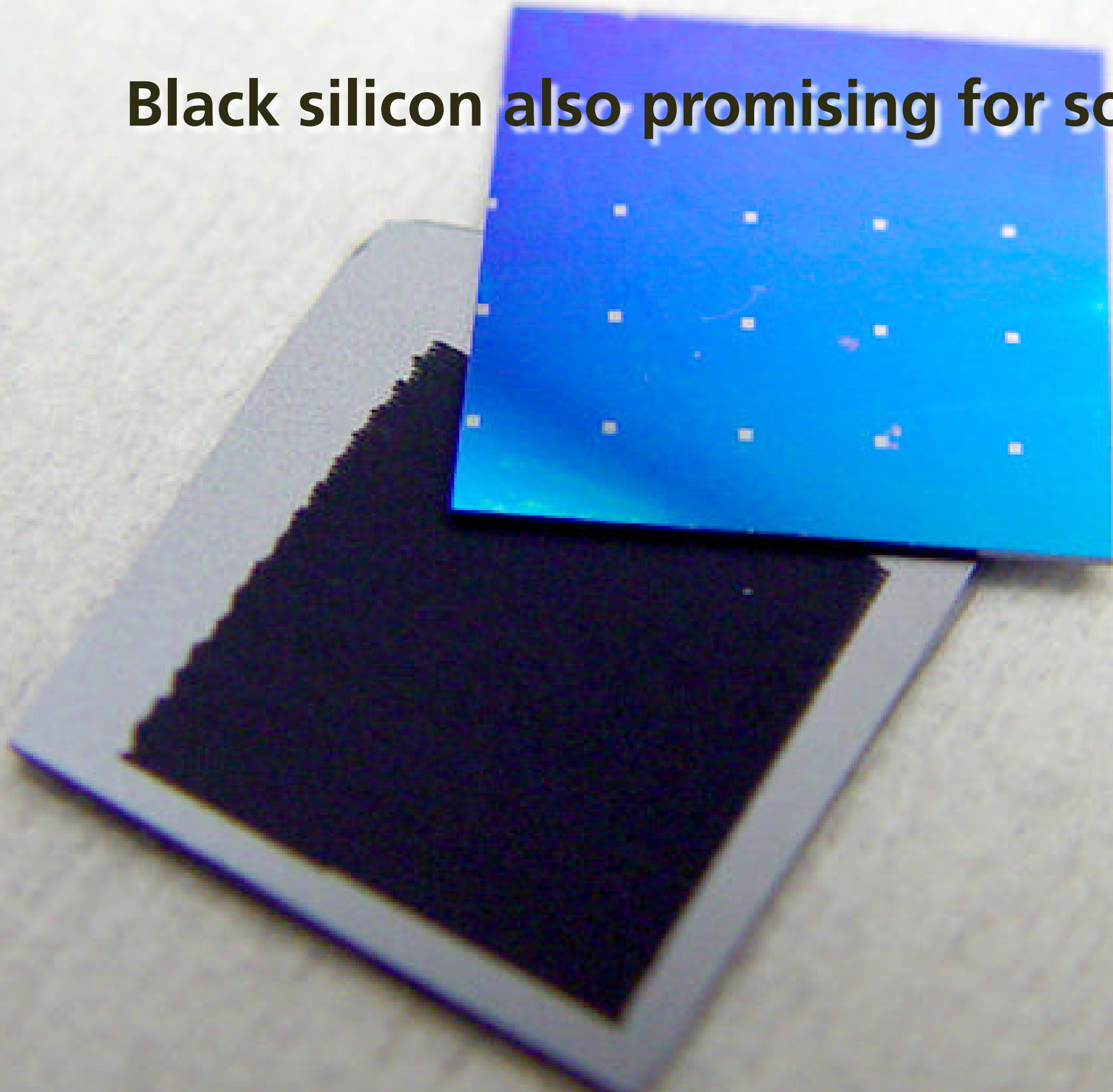
Black silicon photo diode (at 0.5 V bias):

- **100x larger signal in visible (gain!)**
- **10^5 larger signal in infrared**



Black silicon

Black silicon also promising for solar cells



Black silicon

A forest of silicon spikes could revolutionise solar cells and give you painless injections. **Bruce Schechter** peers into the mysterious world of black silicon

TALL, DARK AND STRANGER

WE ALL love stories of serendipity. They seem to hark back to a time when a fogged photographic plate or a filthy Petri dish could change the world. Even today, when financial constraints keep the role of chance to a minimum, science is still sometimes a spontaneous act, a freelance exploration of the unknown. It often starts in front of a blackboard when one scientist says, "I wonder what would happen if . . .", and the other one replies, "Let's give it a try."

The result of one such conversation two years ago in Eric Mazur's laboratory at Harvard University is a new form of silicon ... soot. What started life as ... now has patents ...

semiconductors with a powerful laser. In the early 1990s, Mazur's was the first academic lab in the world to get its hands on a femtosecond laser. This device produces pulses of light that are hundreds of billions of times brighter than the Sun. Its immense power is delivered extremely quickly: each pulse lasts a mere fraction of a trillionth of a second.

These flashes of laser light have provided researchers with a new way to probe the characteristics of many materials (New Scientist, 19 February 2000, p 34). Mazur's group was using the powerful femtosecond pulses to study the surface chemistry of metals. But Her, who is now at the Lawrence Livermore Laboratory in California, had been wondering for years what ... would do to semiconductors like ... tried it, so there

around the laboratory," he claims.

Well, it was almost the only reason. A short laser pulse will break down SF_6 into sulphur and fluorine radicals, which will attack a silicon substrate. "Hydrogen fluoride is used to etch silicon. So we thought maybe the SF_6 would decompose and then the fluorine would somehow react with the silicon," Mazur explains.

With no clearer idea than this, th... researchers began firing 100-femtosecon... pulses of laser light through the wind... of their chamber, through the SF_6 gas a... onto the shiny silicon wafer. After fi... about 100 pulses they cracked the se... the chamber and removed the wafer... saw a tiny black spot at the focal p... the laser beam. A burn, perhaps... that Mazur knew that silicon does... "You can get silicon oxide, bu... black," he says. So what was go...

New Scientist 13, 34 (2001)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