Hyperdoped and microstructured silicon for solar energy harvesting

PIERS 2012
Kuala Lumpur, Malaysia, 28 March 2012

Renee Sher

Yu-Ting Lin

Kasey Philips

Ben Franta

eric_mazur

and also....

Marc Winkler
Eric Diebold
Haifei Albert Zhang
William Whitney
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. Elizabeth Landis
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)
Matthew Smith (MIT)

Prof. Augustinus Asenbaum (Vienna)

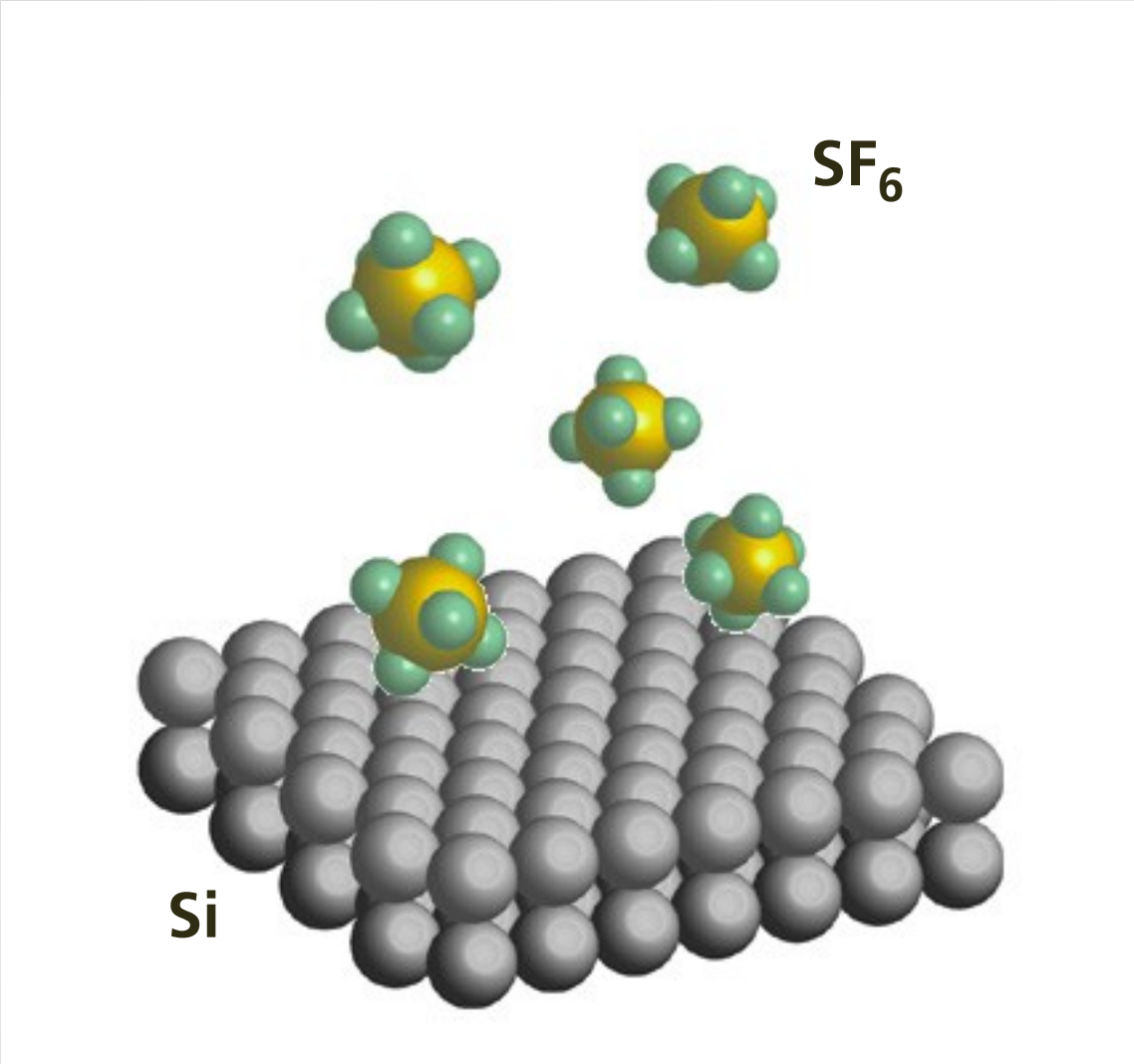
Dr. François Génin (LLNL)
Mark Wall (LLNL)

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

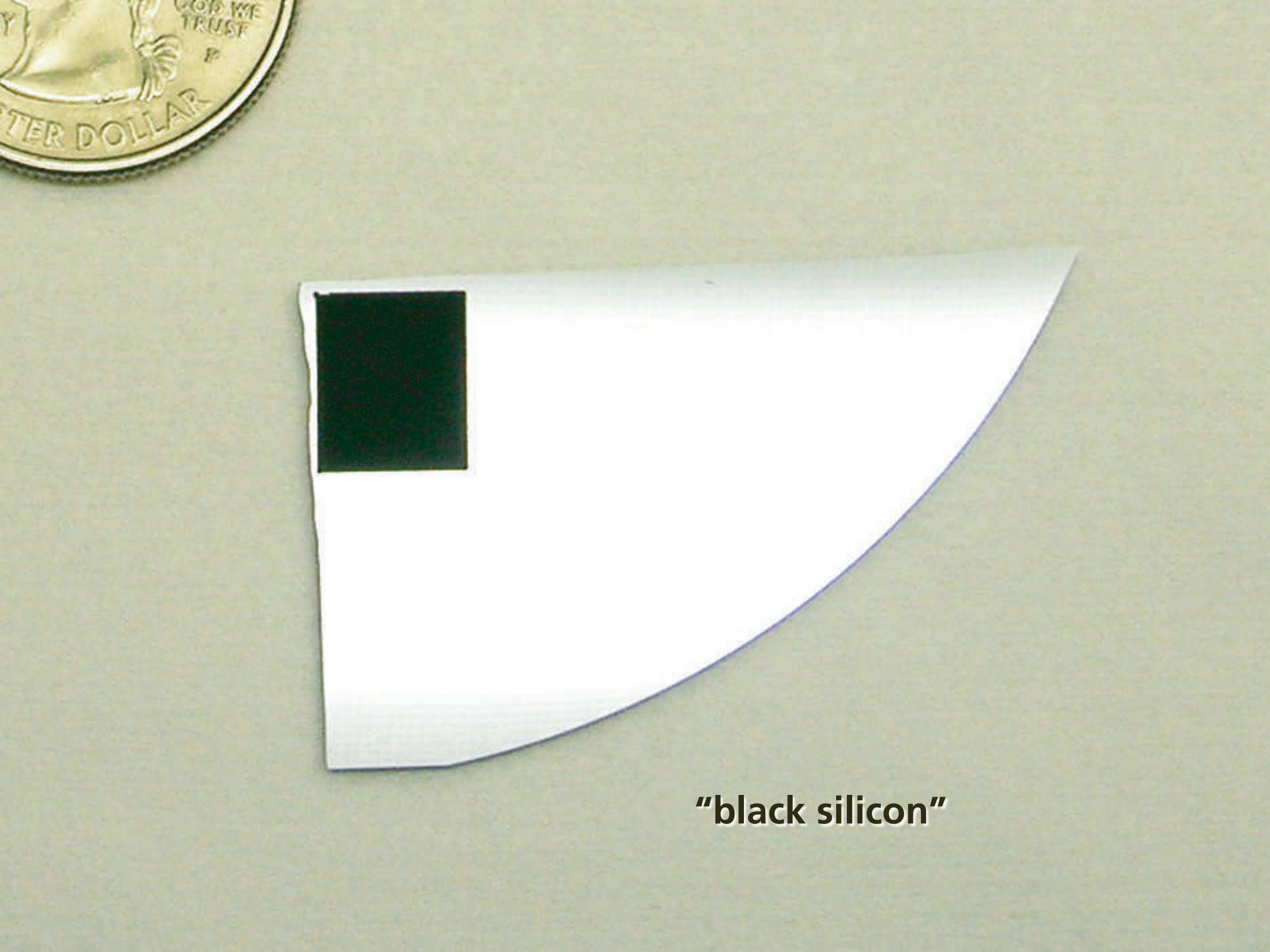
Dr. Pat Maloney (NVSED)

Dr. Jeffrey Warrander (ARDEC)

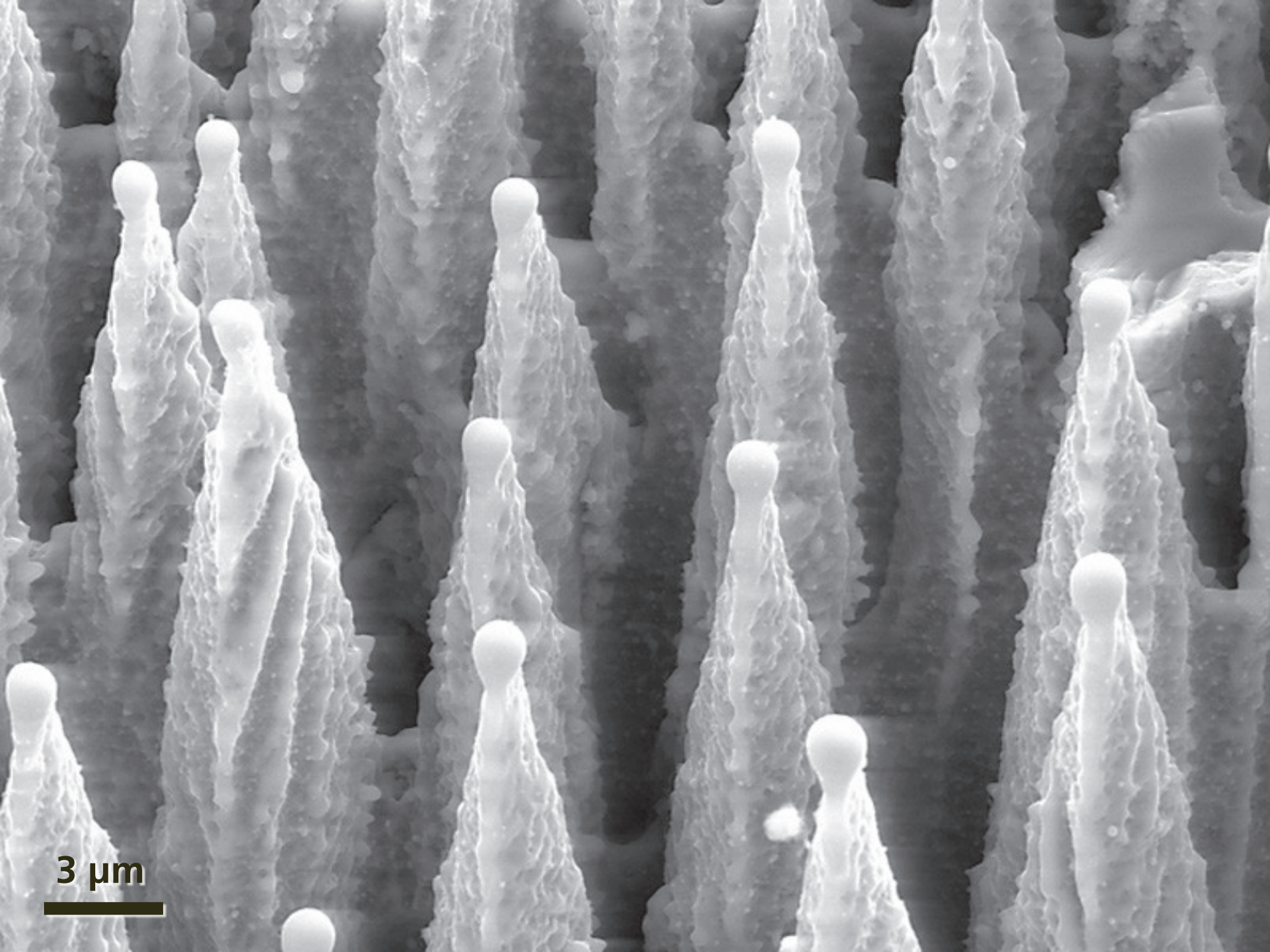
...and the people at SiOnyx



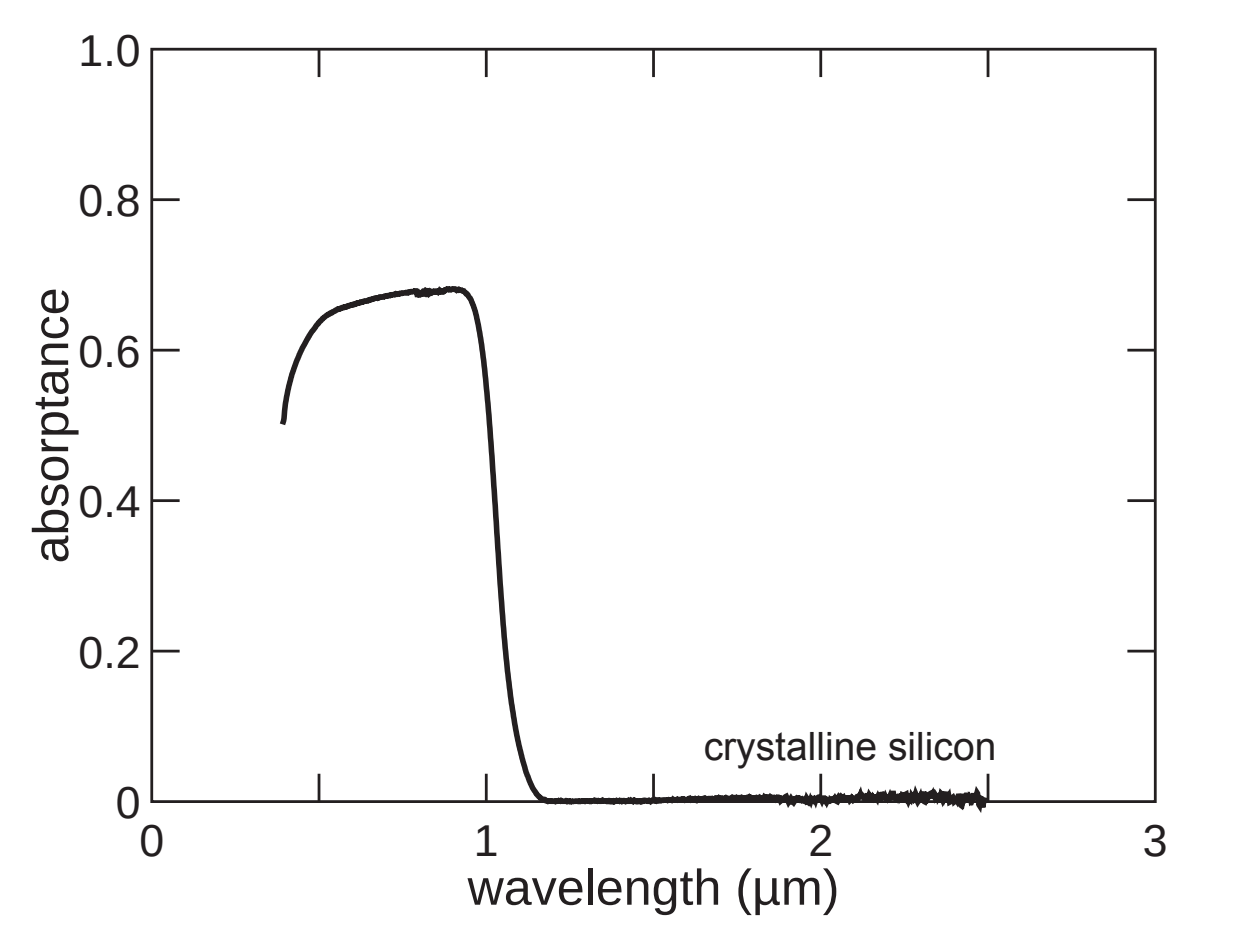
irradiate with 100-fs 10 kJ/m^2 pulses



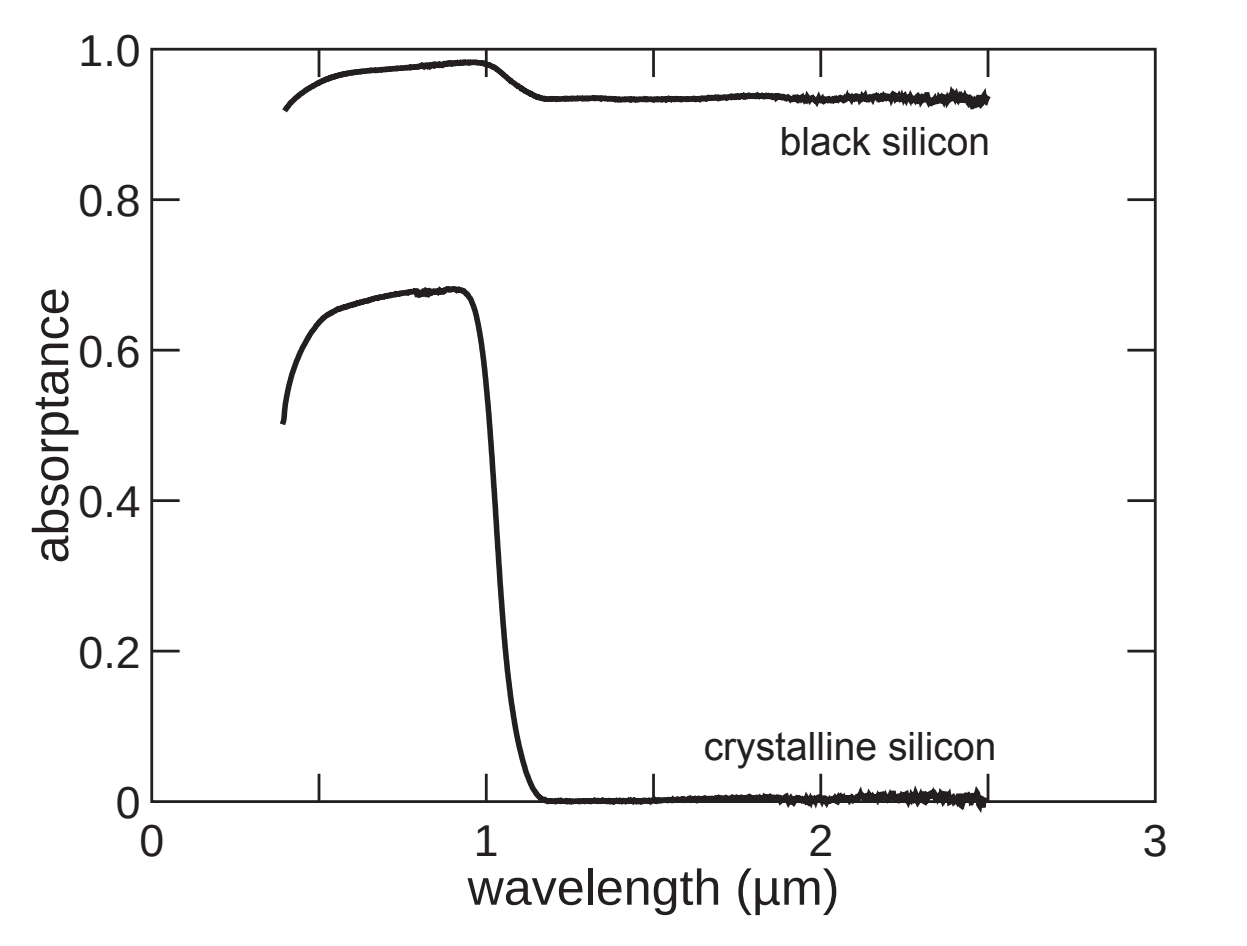
“black silicon”

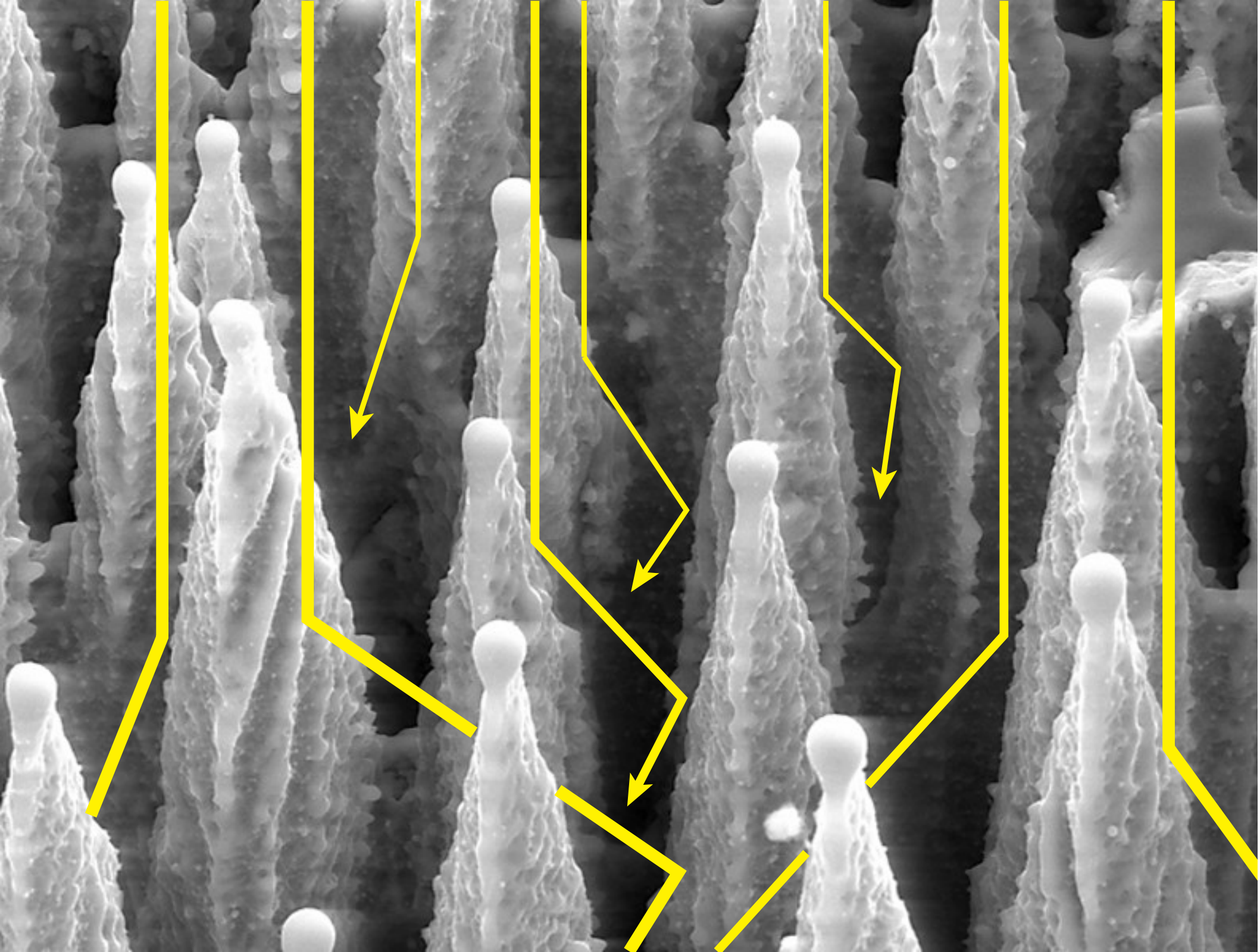

3 µm

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

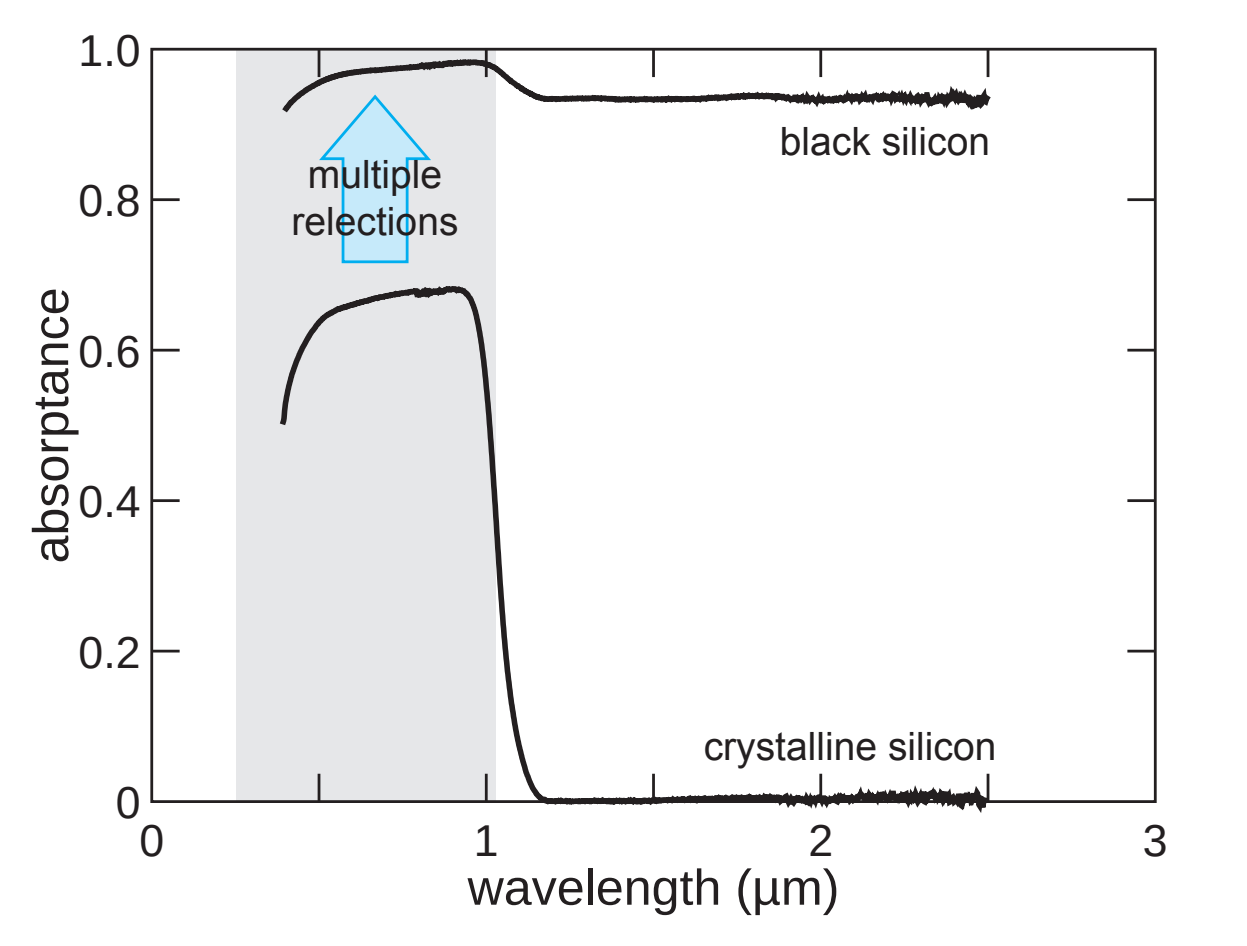


absorptance ($1 - R_{int} - T_{int}$)

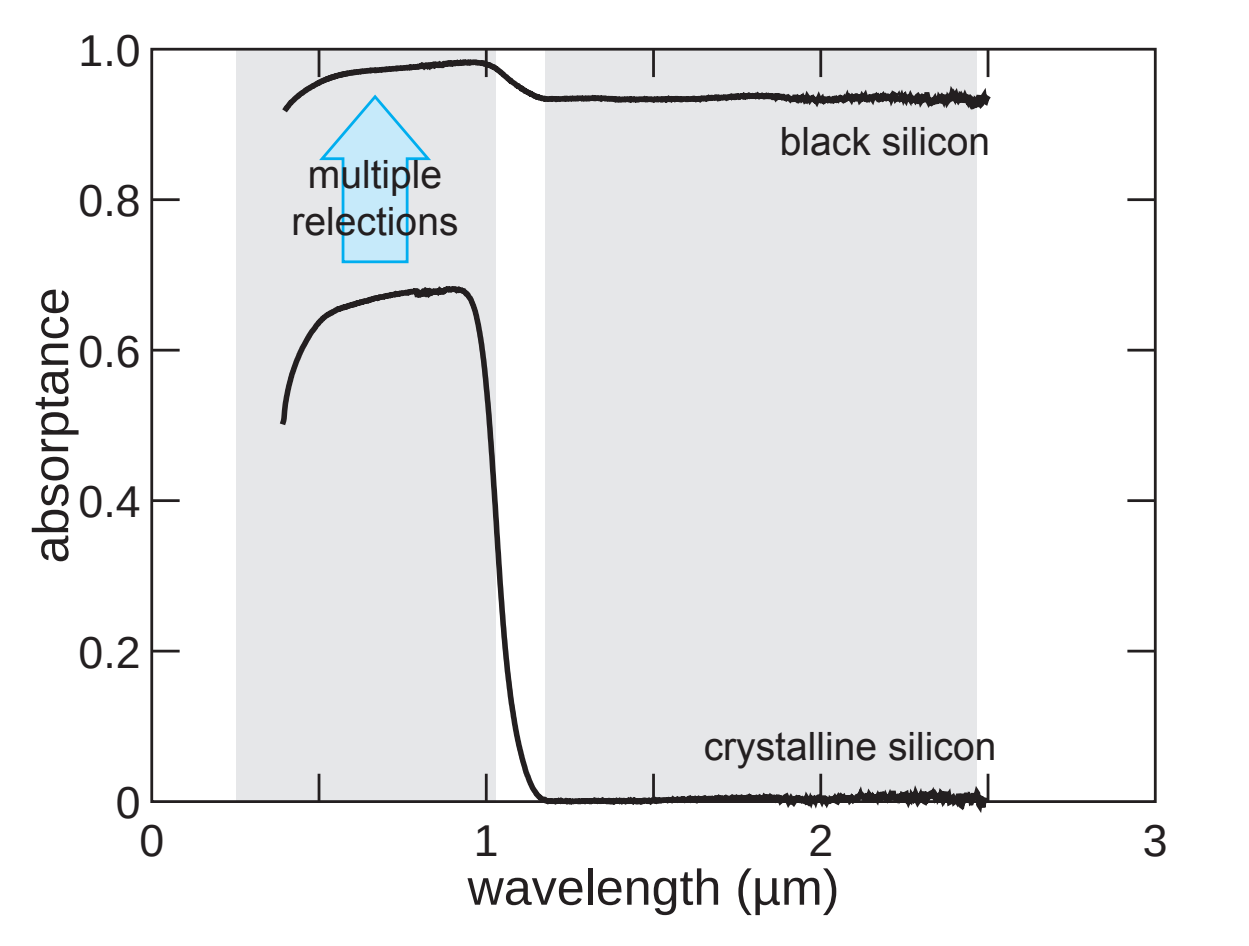




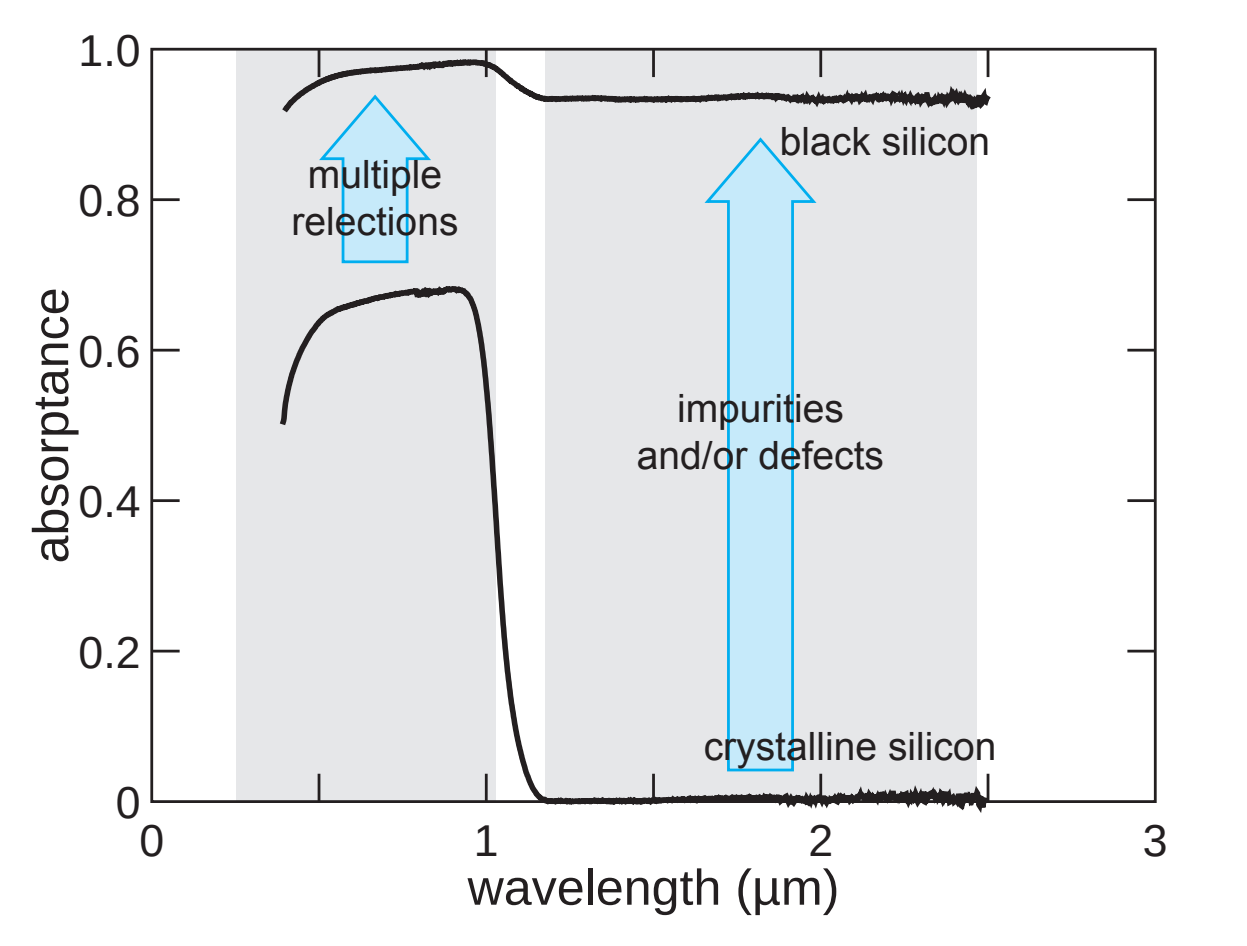
absorptance ($1 - R_{int} - T_{int}$)

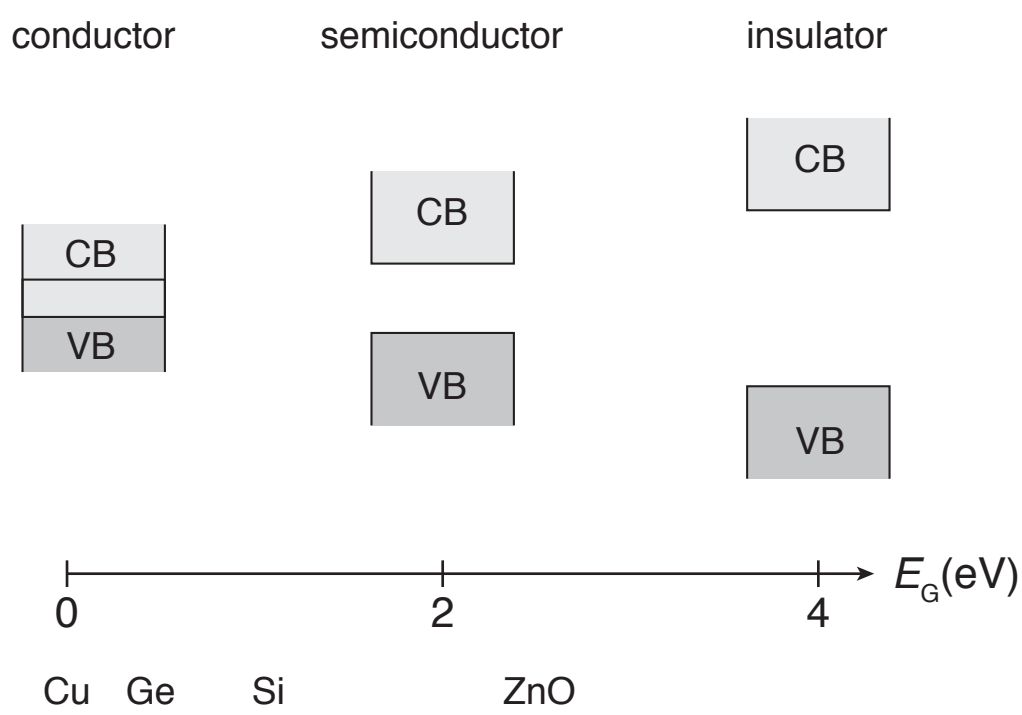


absorptance ($1 - R_{int} - T_{int}$)

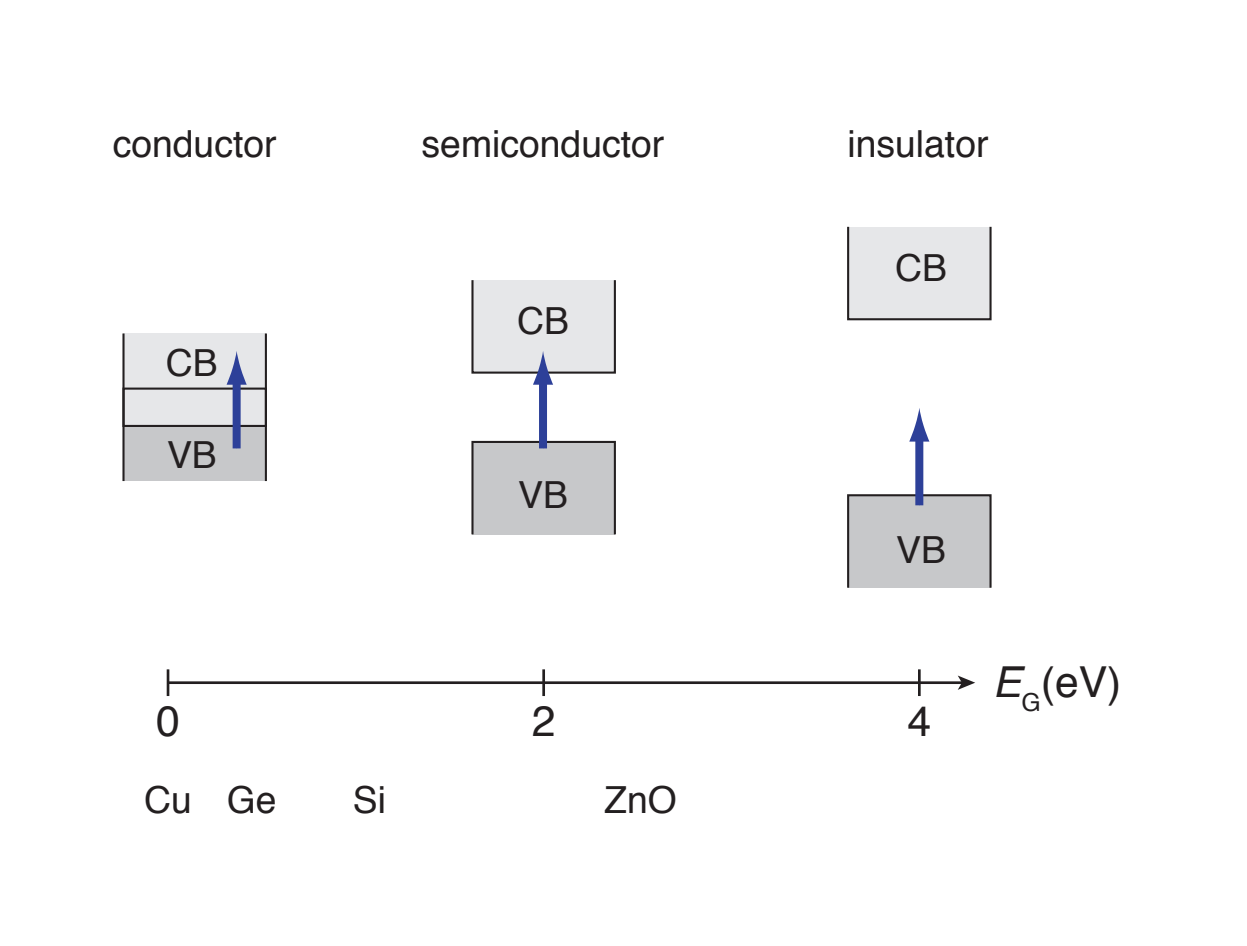


absorptance ($1 - R_{int} - T_{int}$)

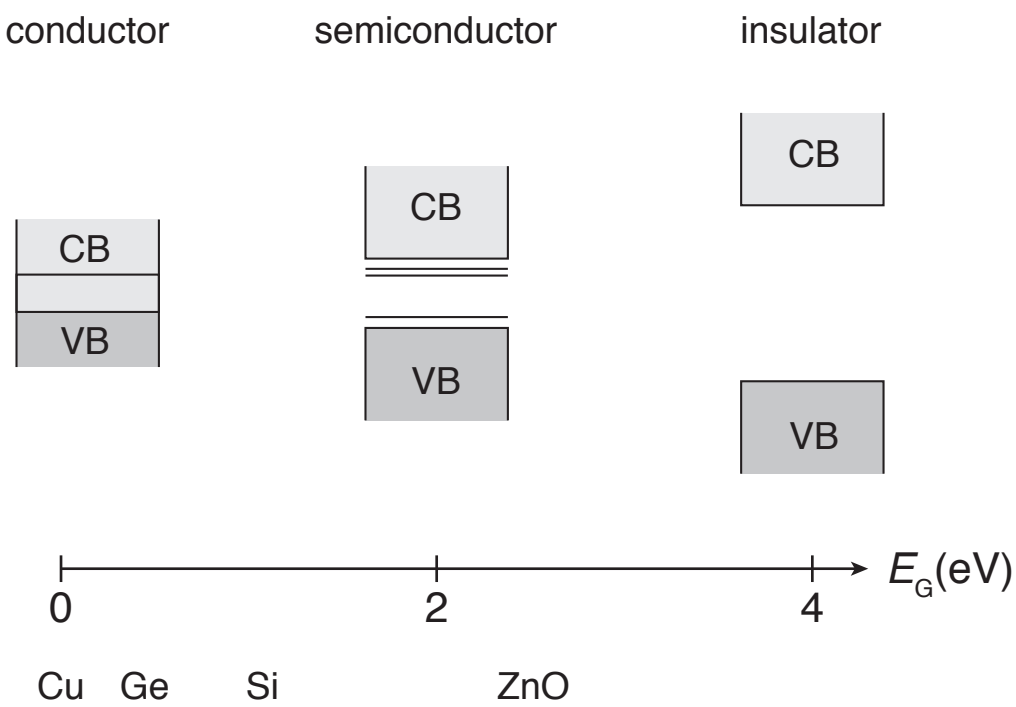



conductor
semiconductor
insulator
CB
VB
CB
VB
CB
VB
0
2
4
E_G(eV)
Cu
Ge
Si
ZnO

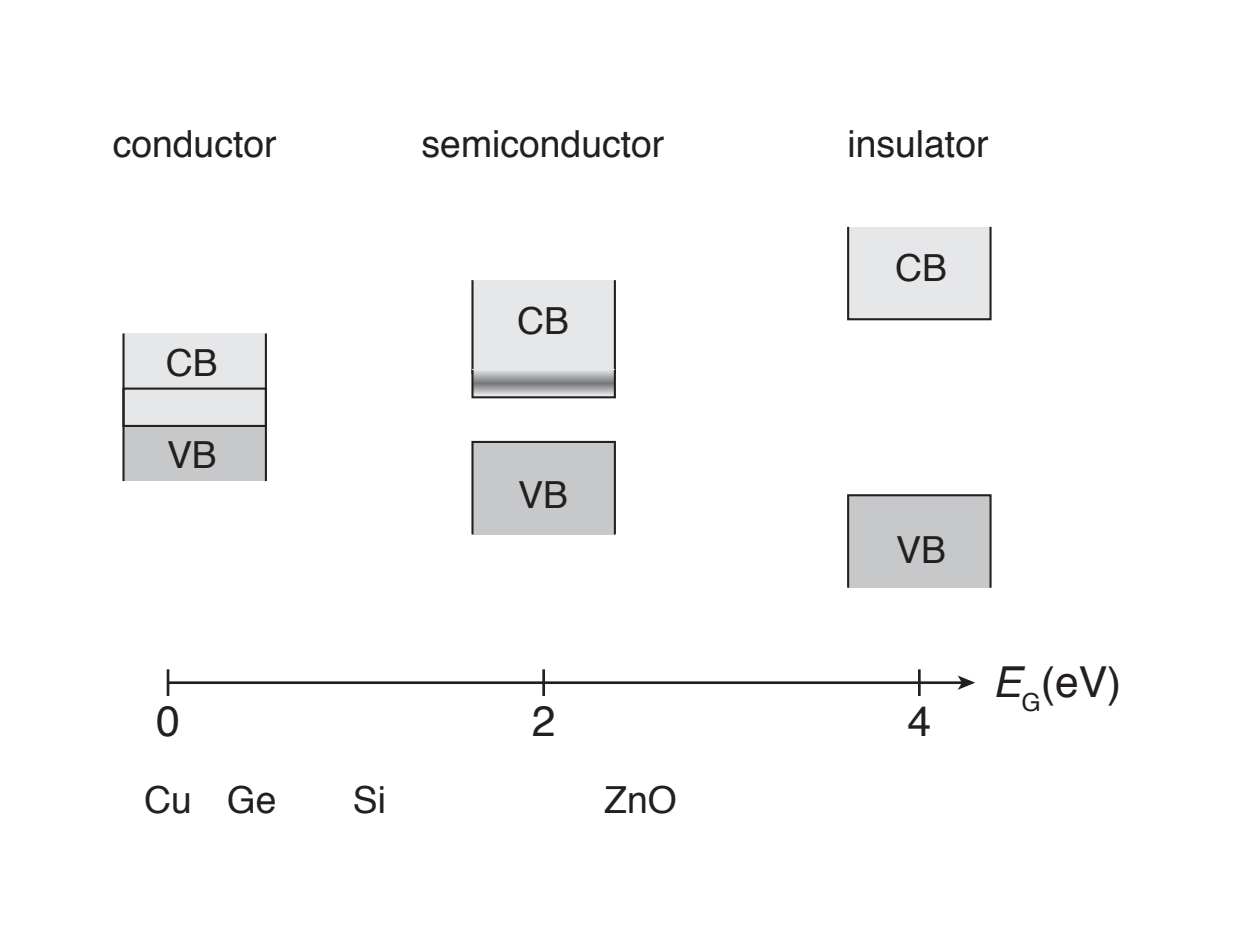
gap determines optical and electronic properties



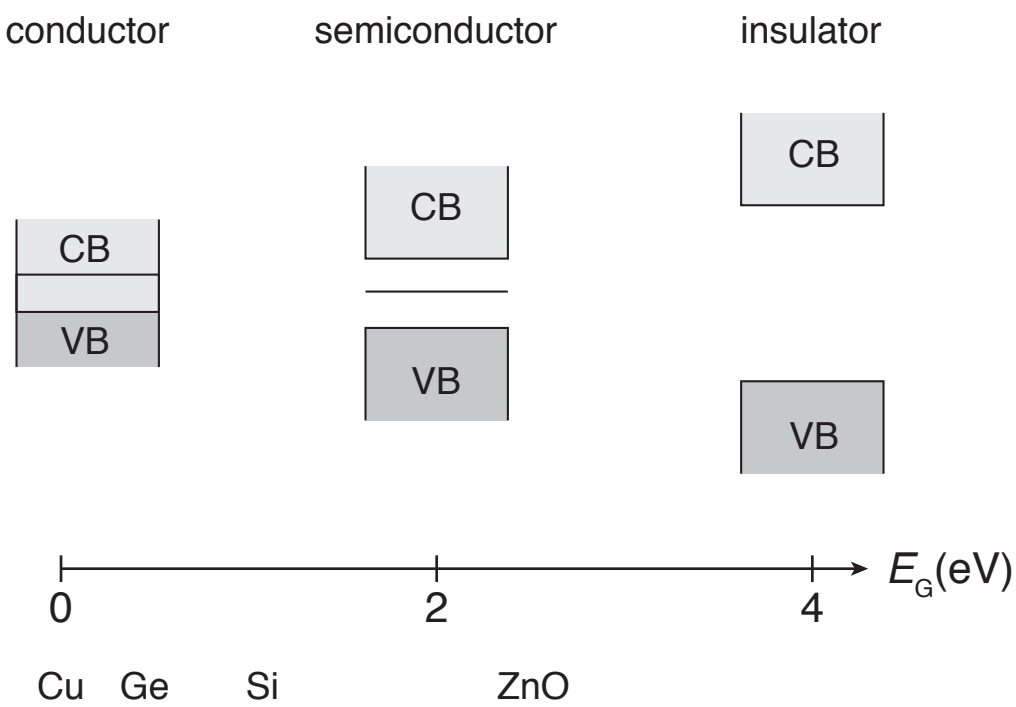
shallow-level dopants control electronic properties



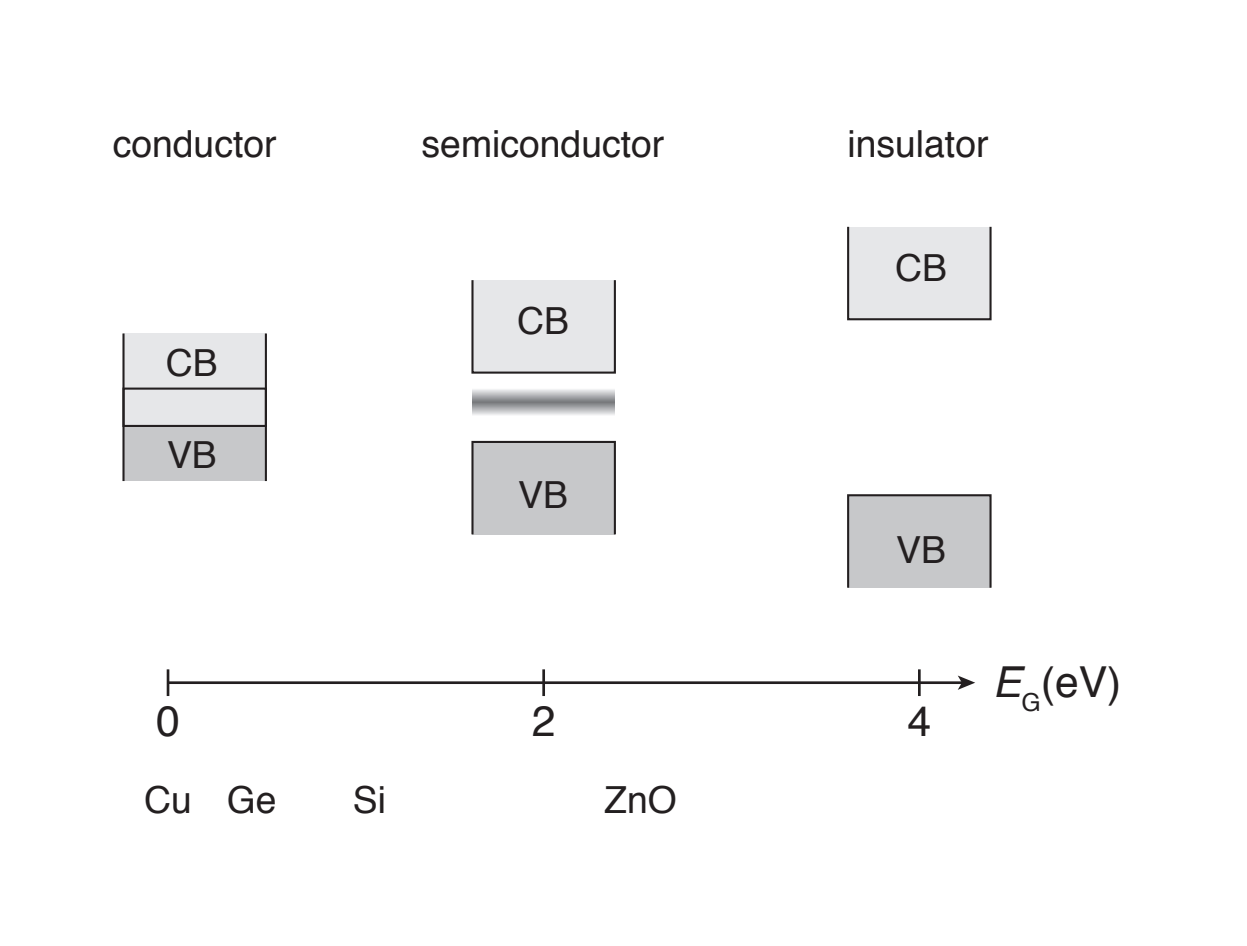
shallow-level dopants control electronic properties



deep-level dopants typically avoided



femtosecond laser-doping gives rise to intermediate band



substrate/dopant combinations

dopants:

I																	VIII
H	II											III	IV	V	VI	VII	He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe

substrates:

Si

substrate/dopant combinations

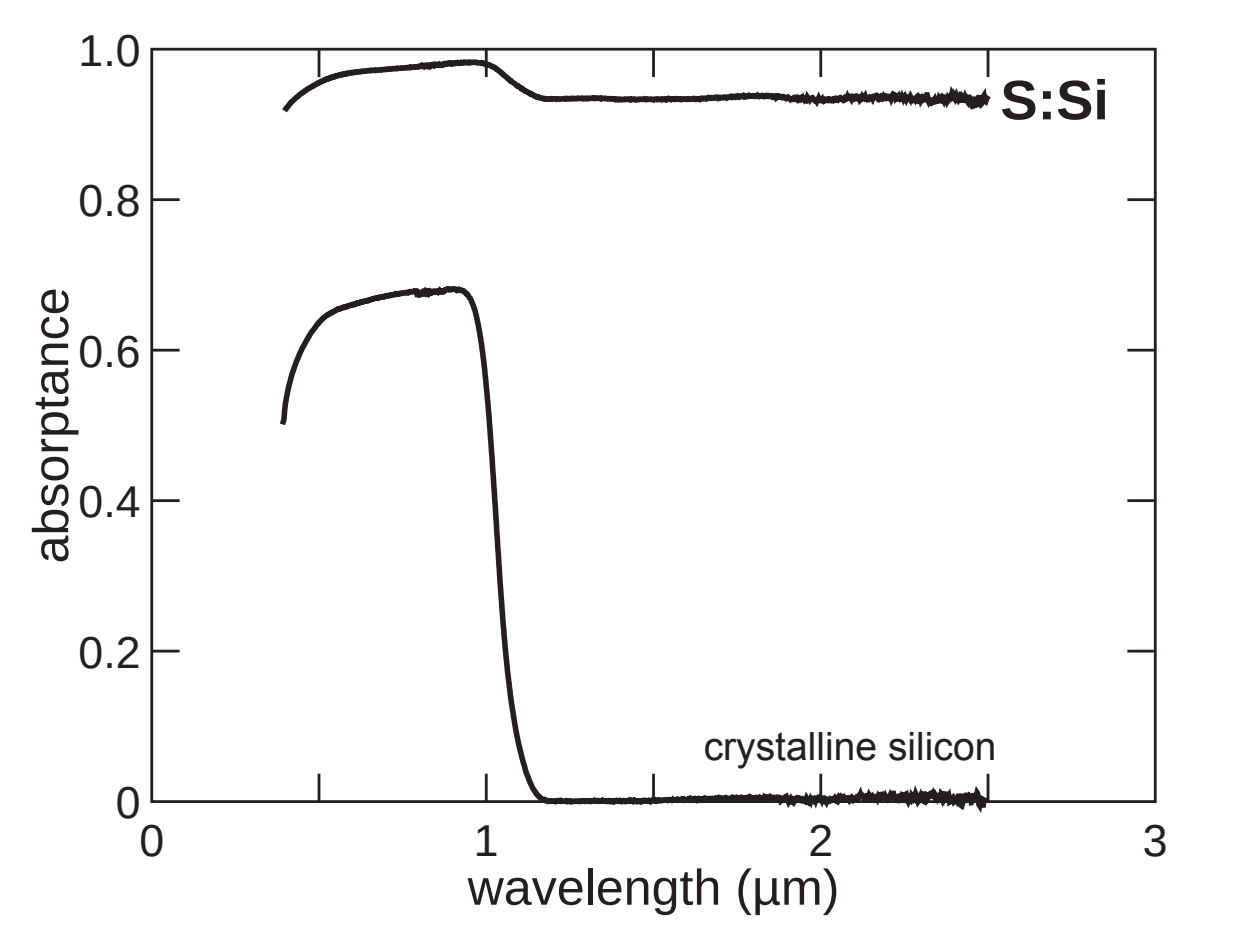
dopants:

I																	VIII
H	II											III	IV	V	VI	VII	He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe

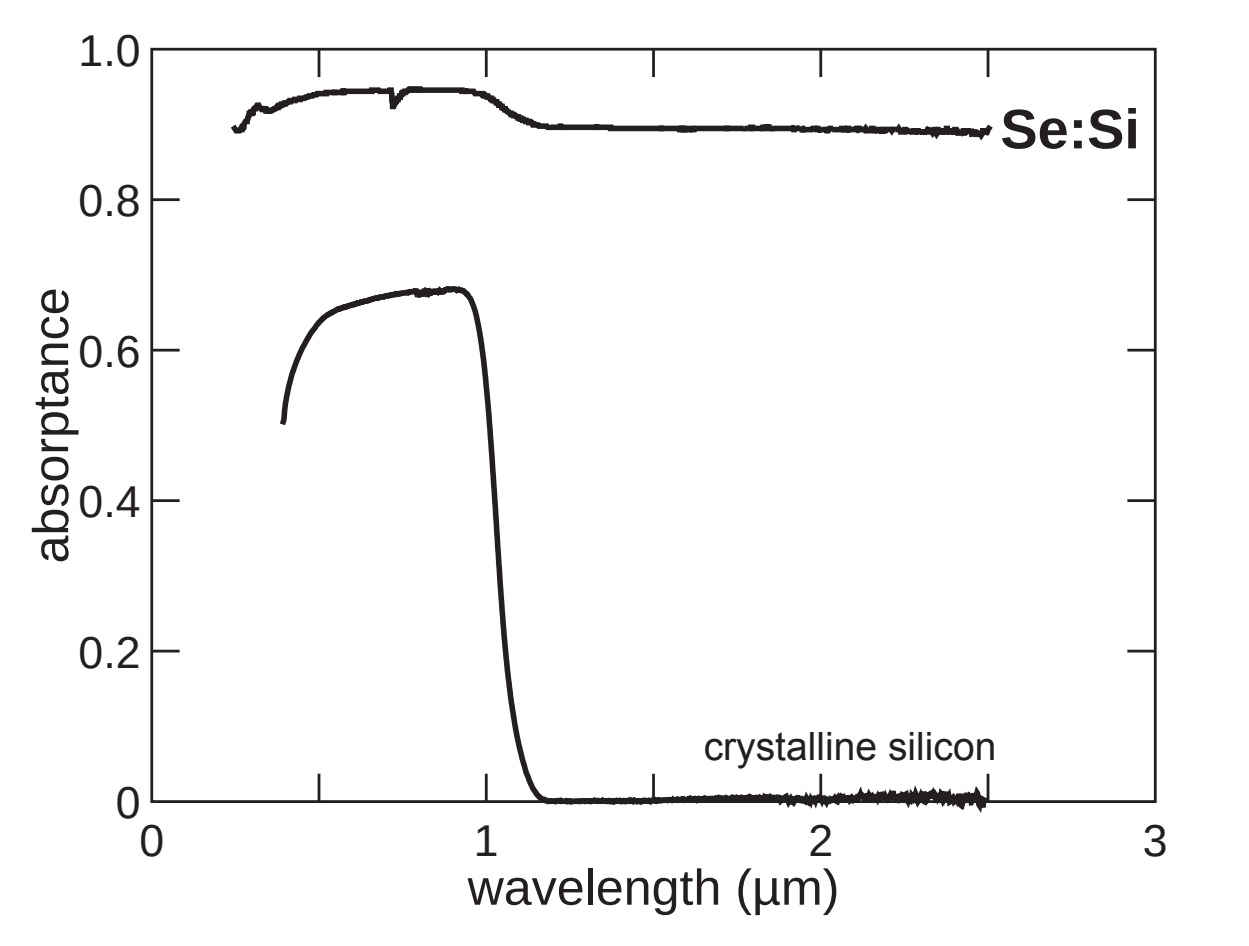
substrates:

Si

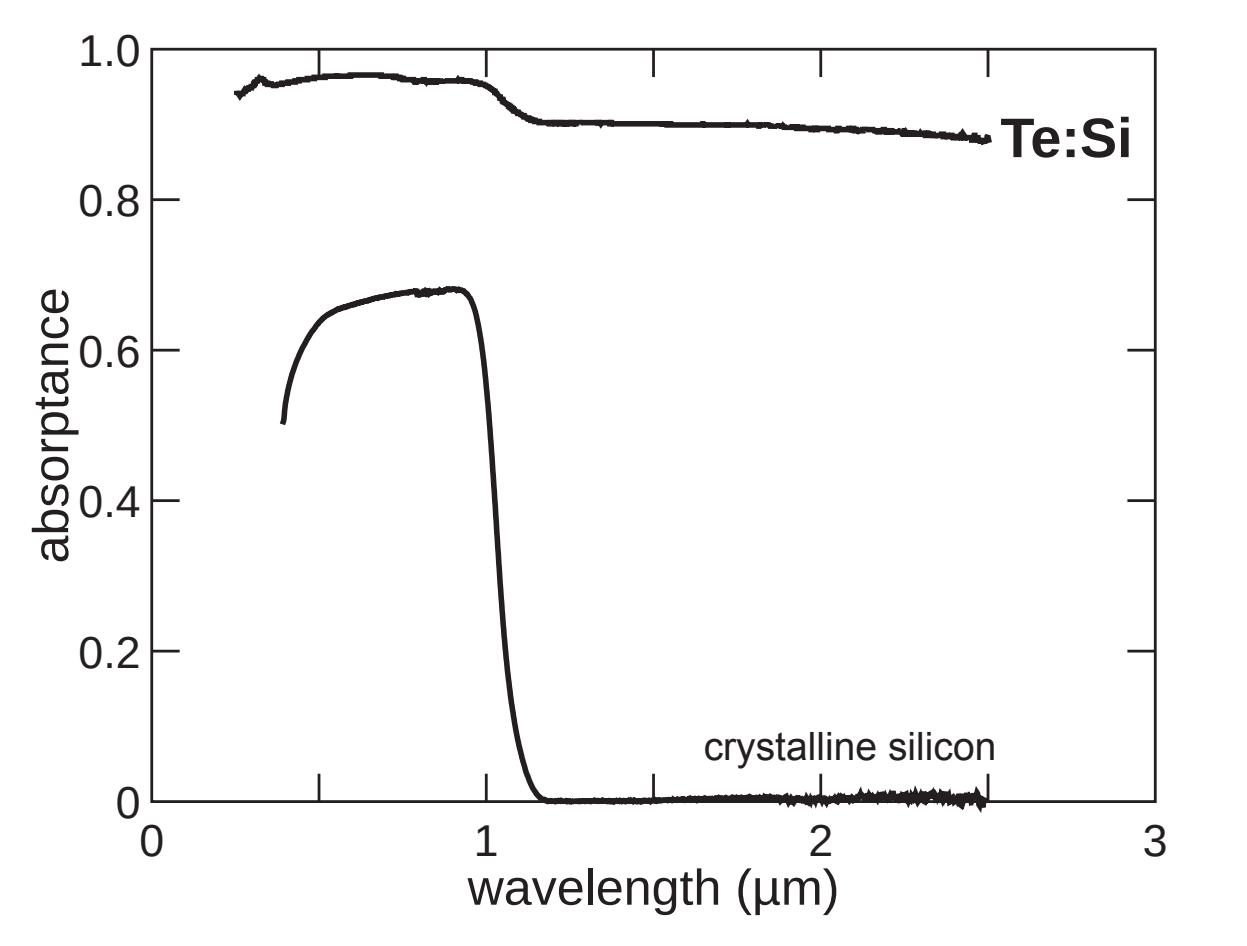
absorptance ($1 - R_{int} - T_{int}$)

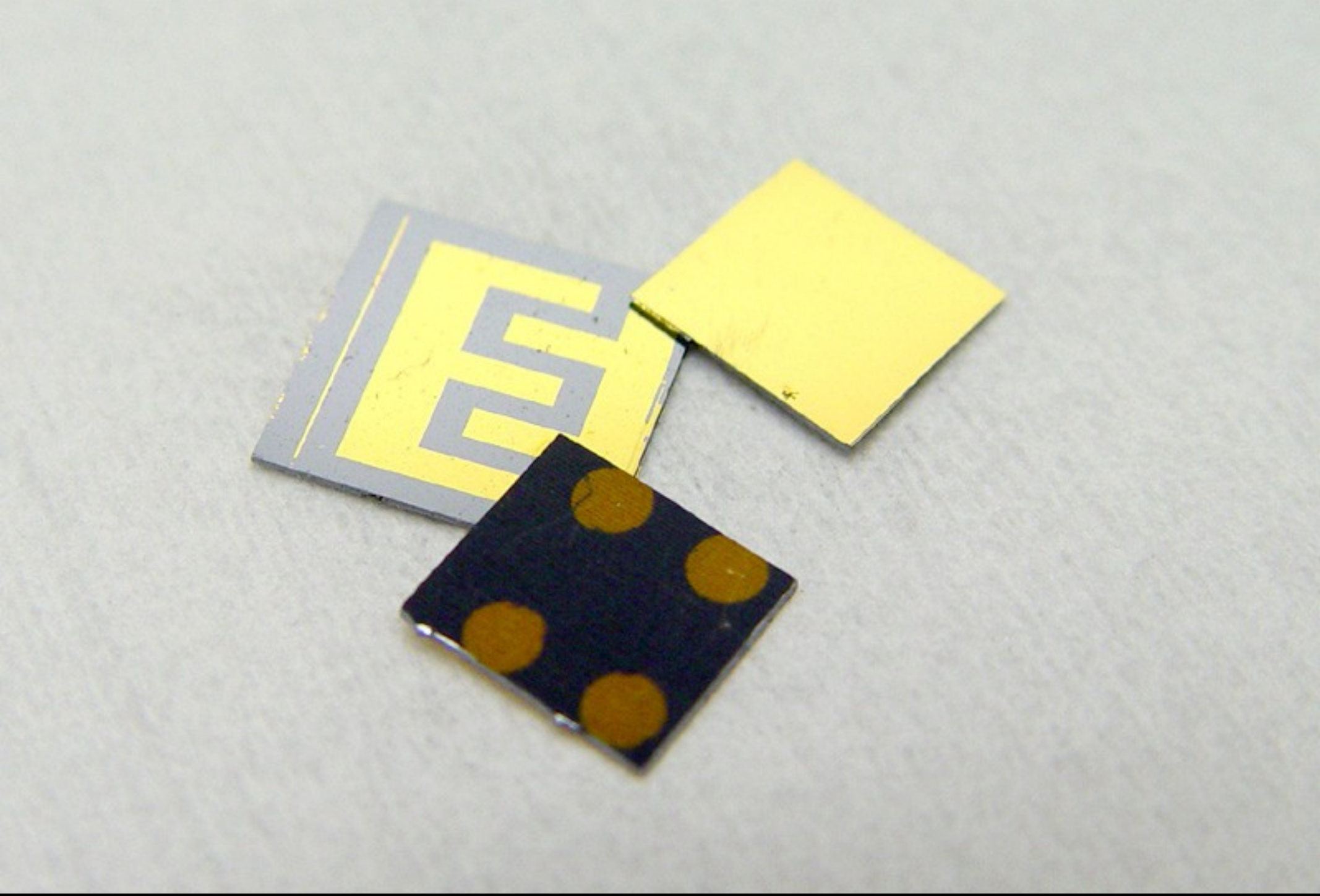


absorptance ($1 - R_{int} - T_{int}$)

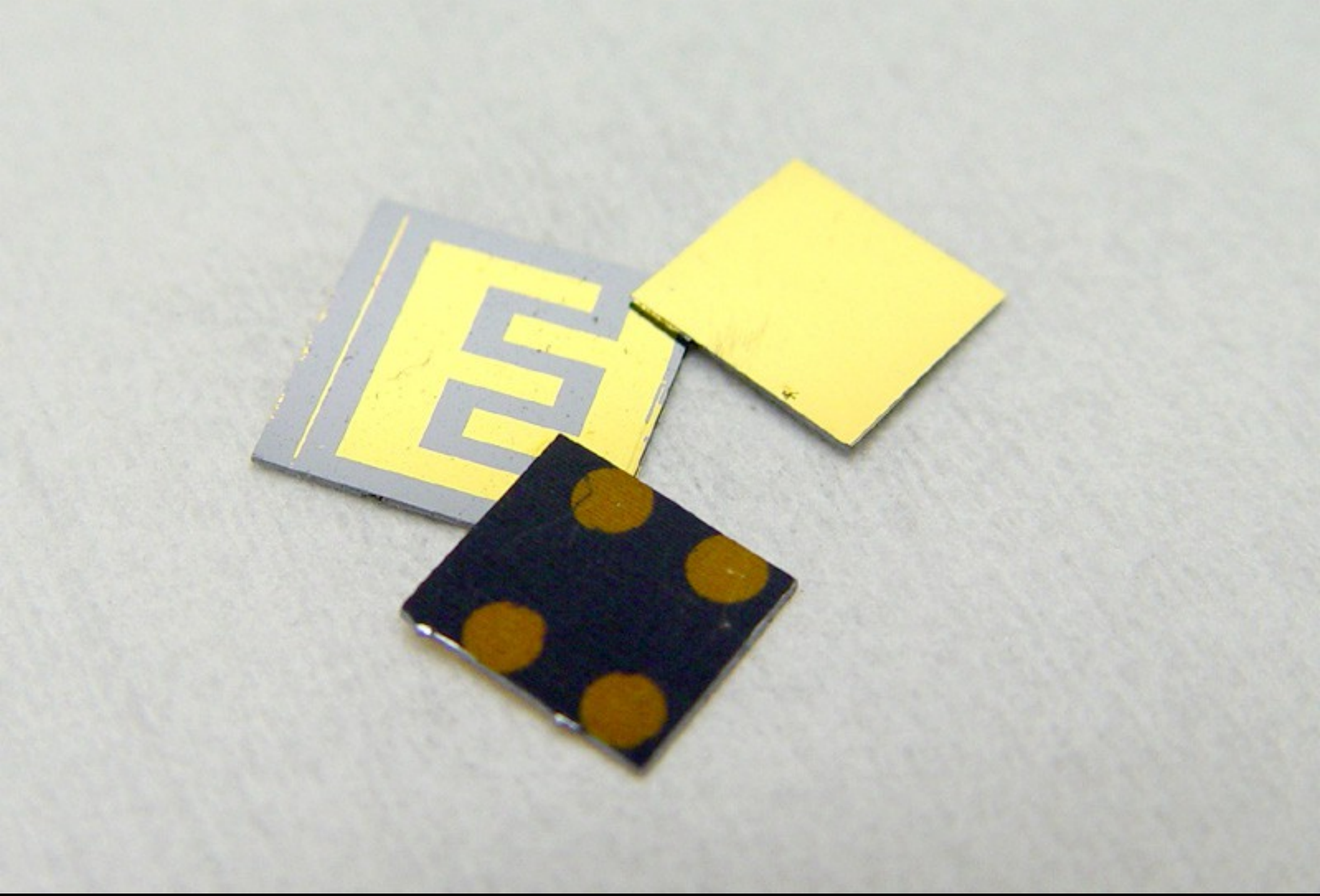


absorptance ($1 - R_{int} - T_{int}$)



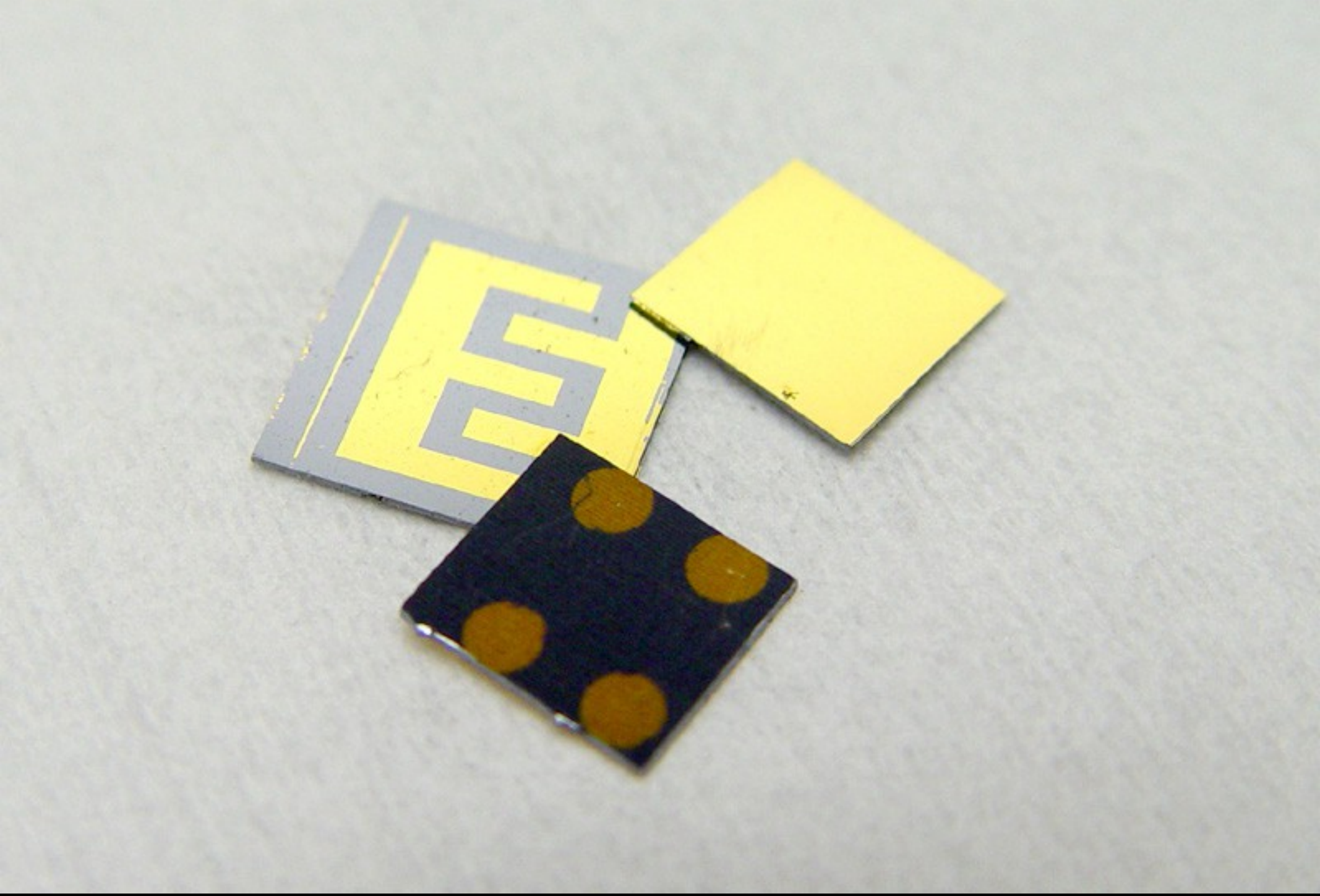


1 structure

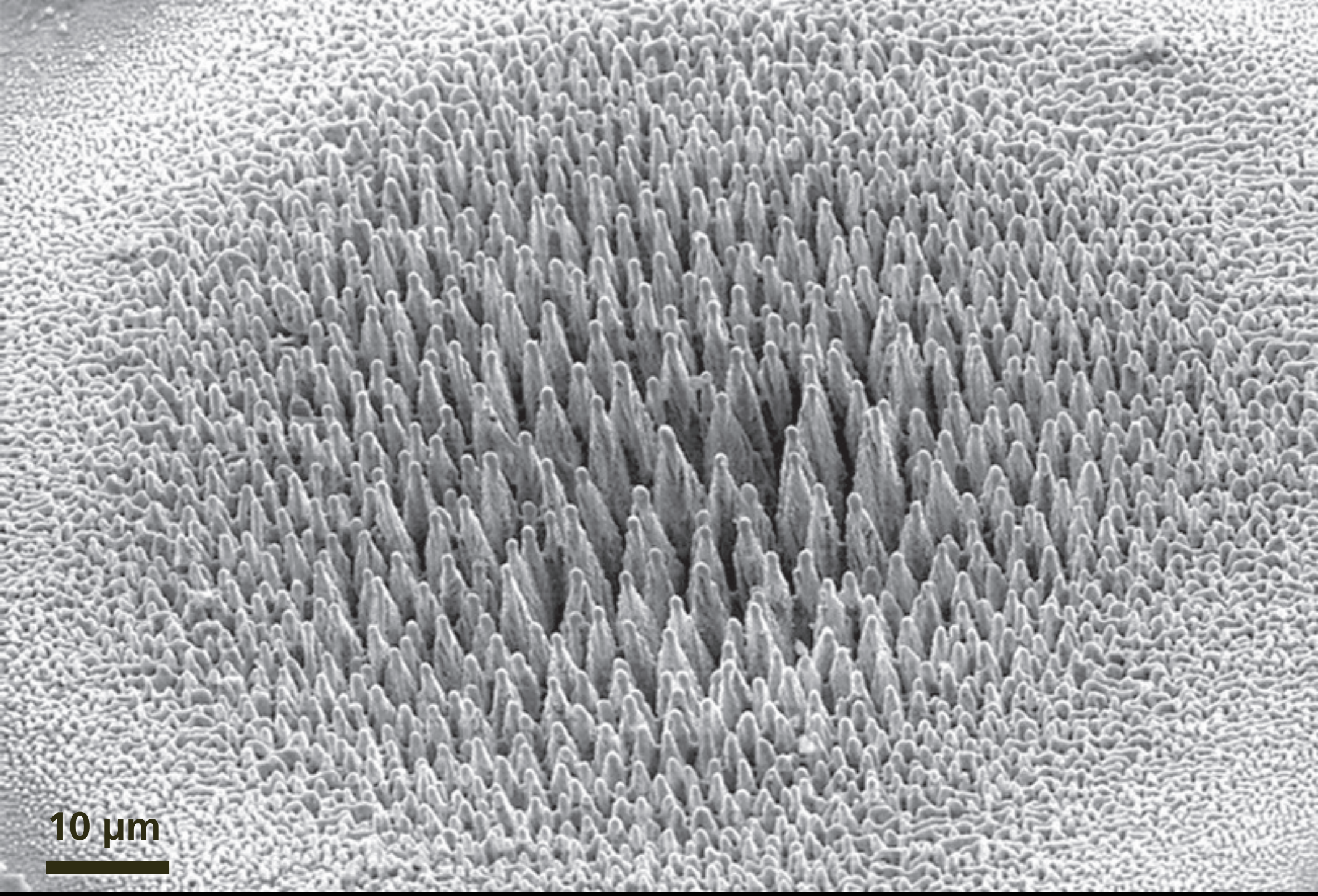


1 structure

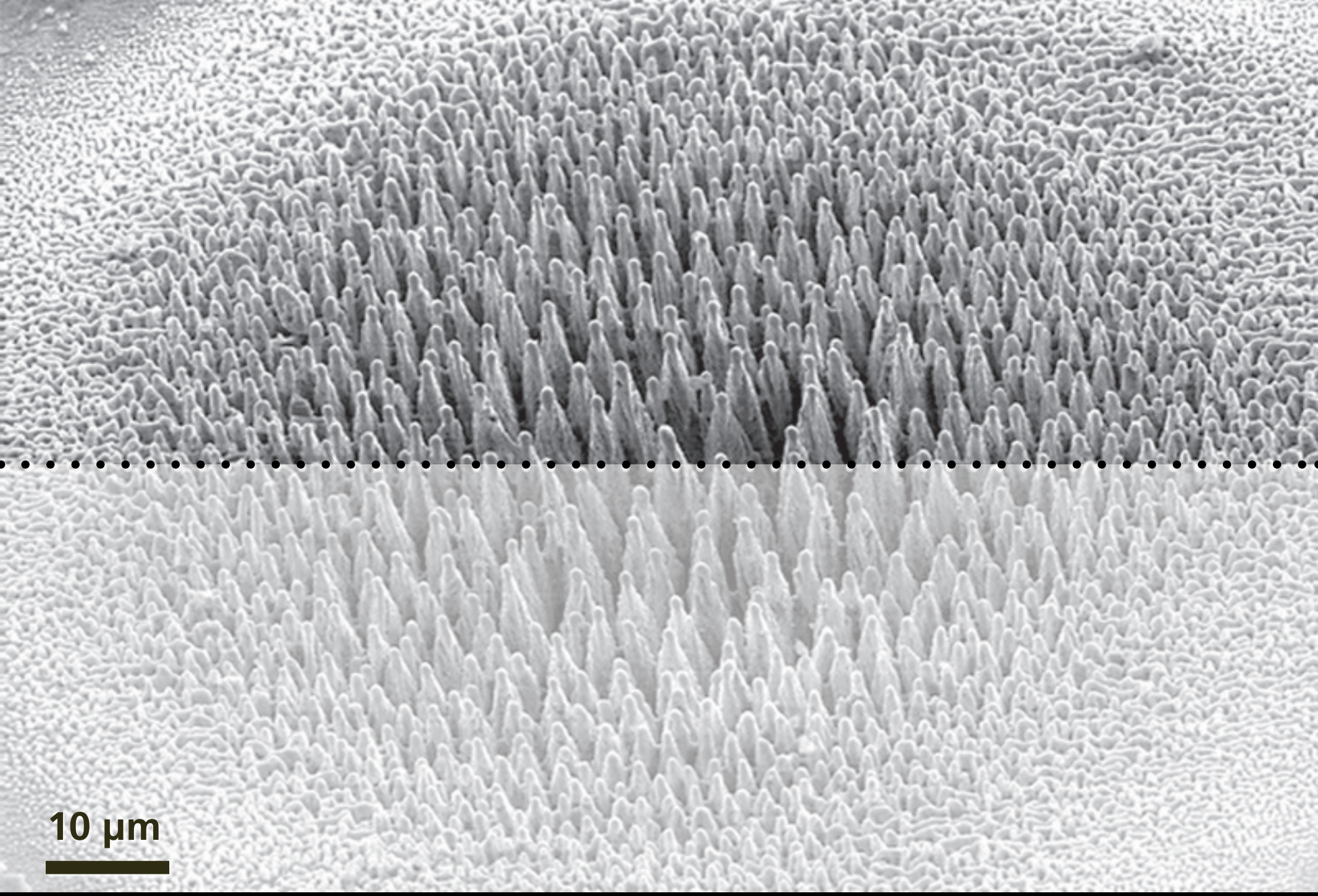
2 OE properties



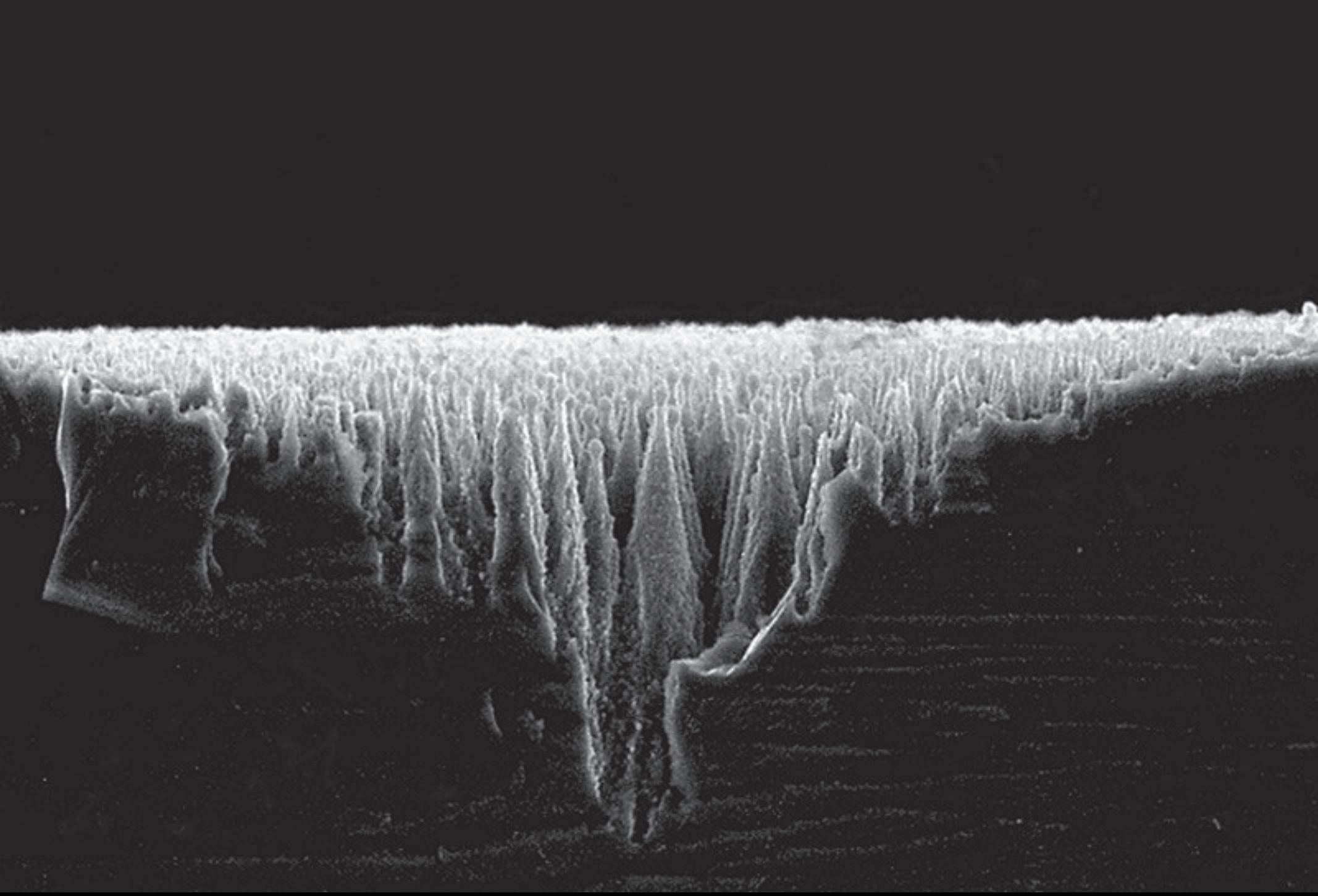
1 structure 2 OE properties 3 devices



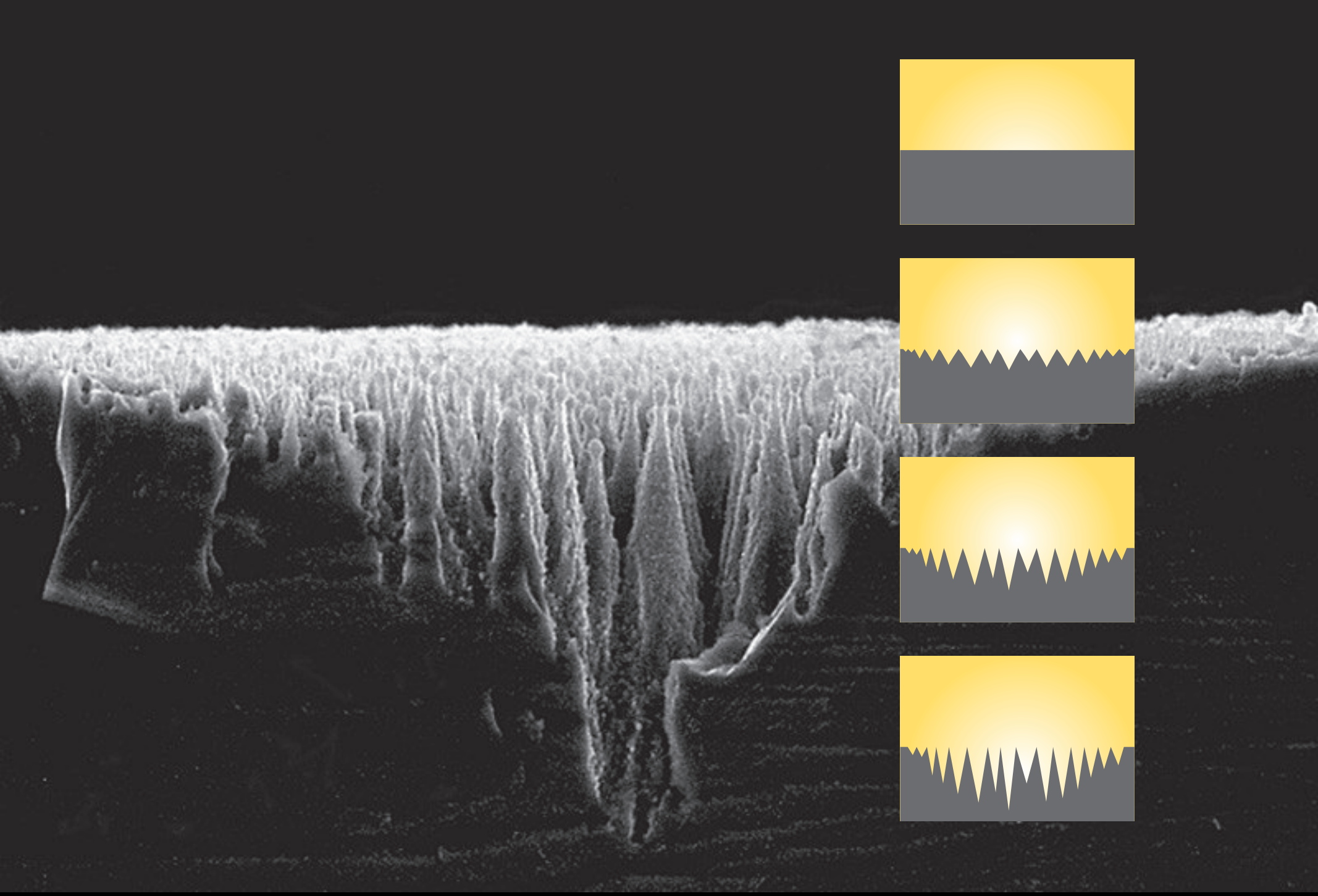
1 structure



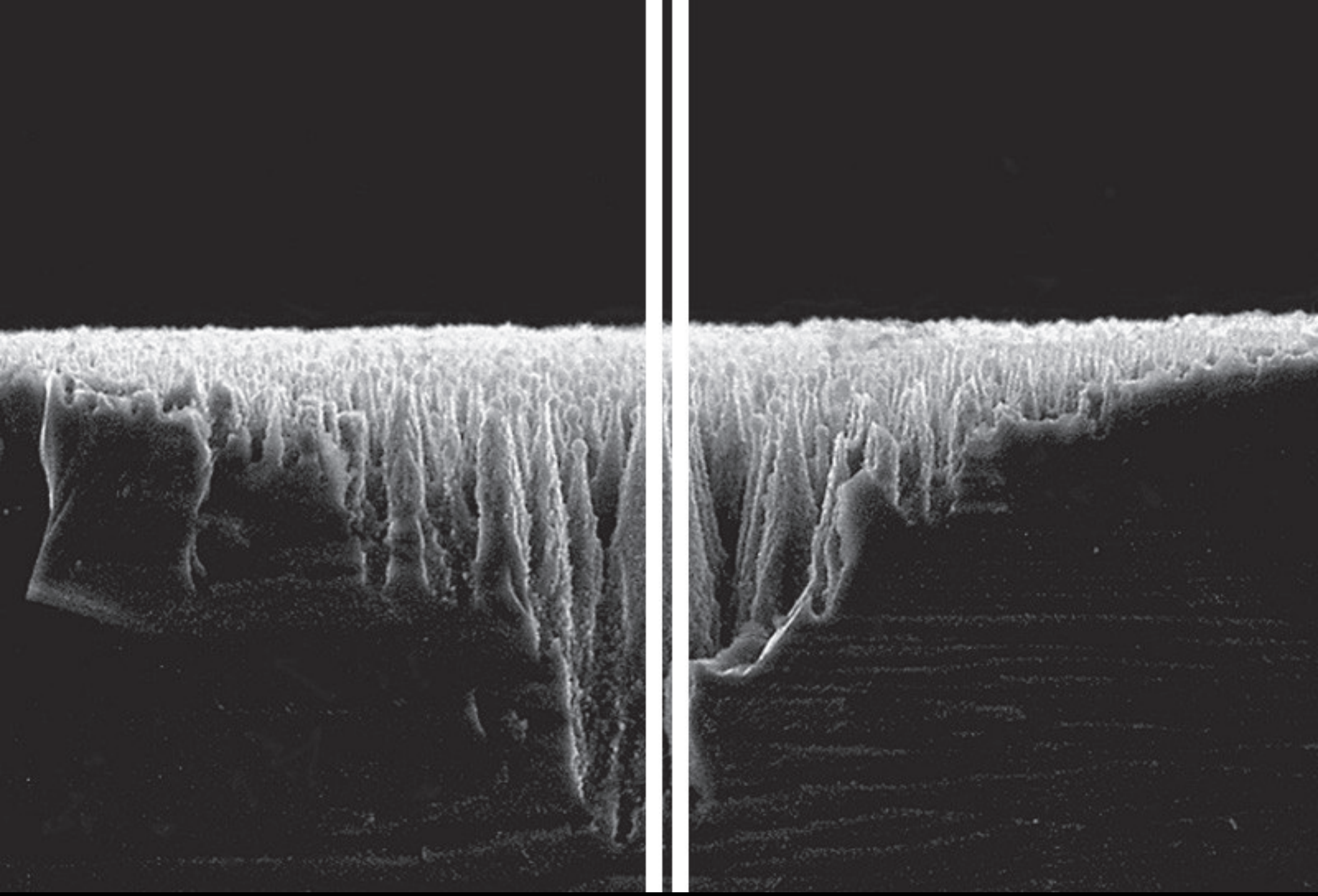
1 structure



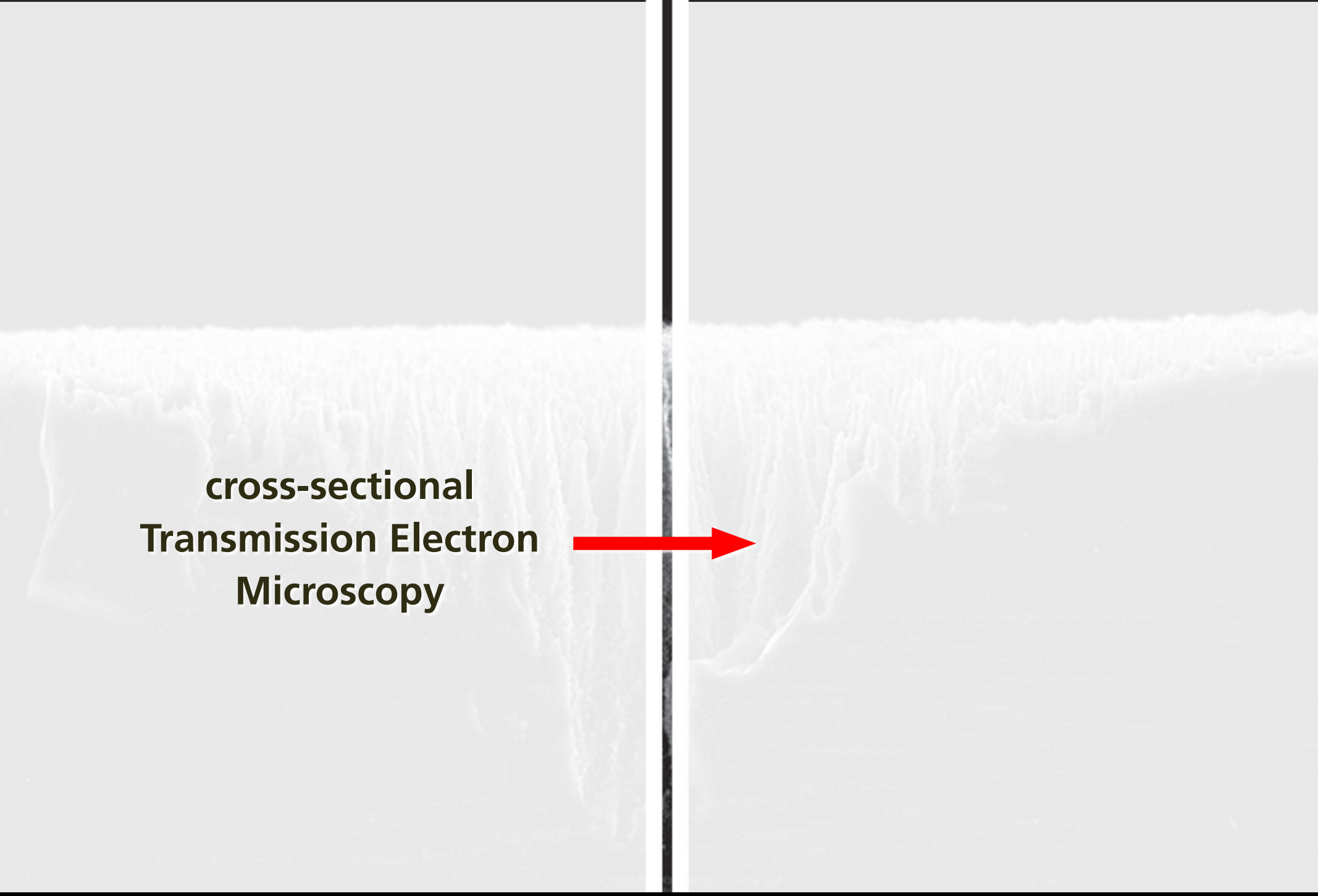
1 structure



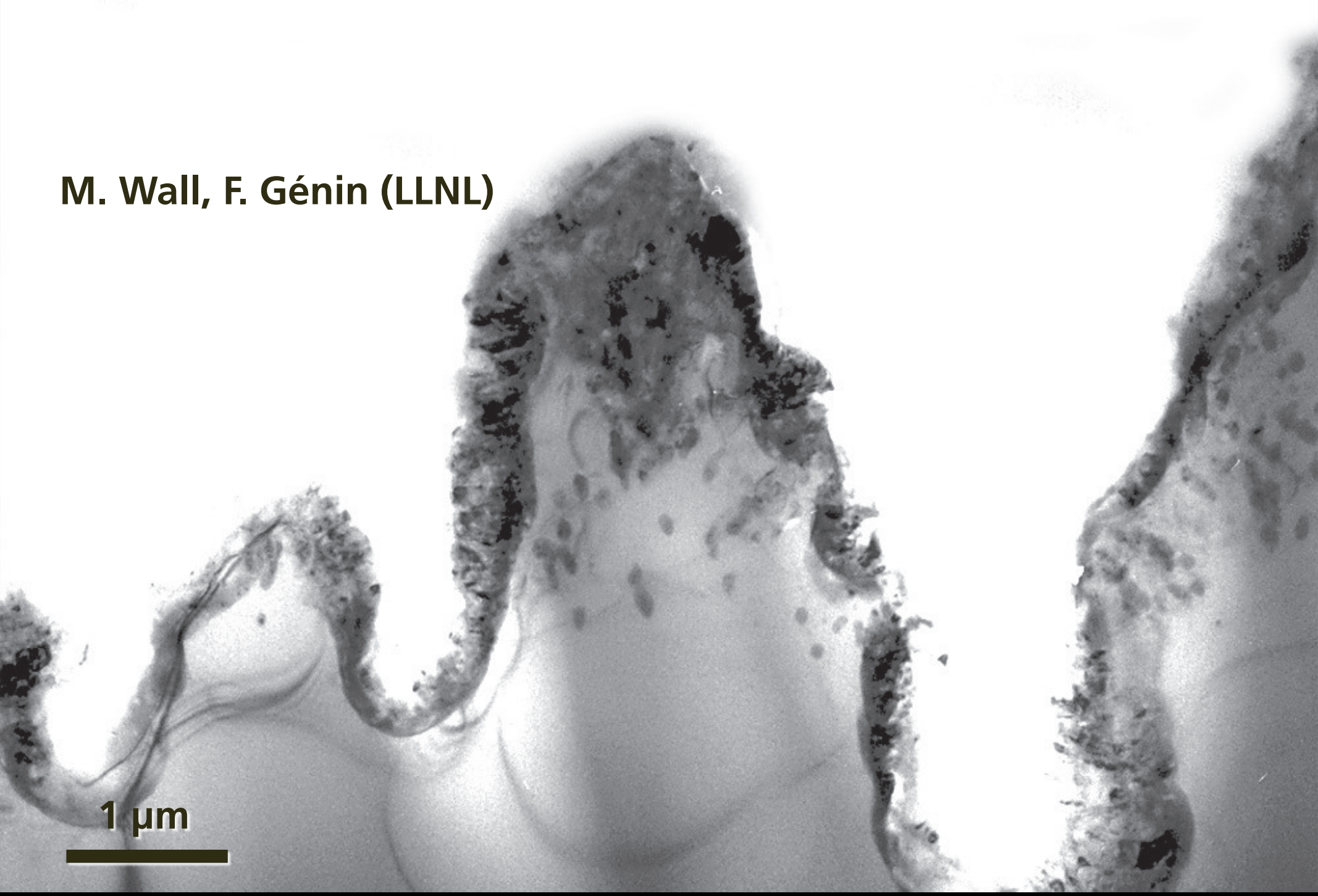
1 structure



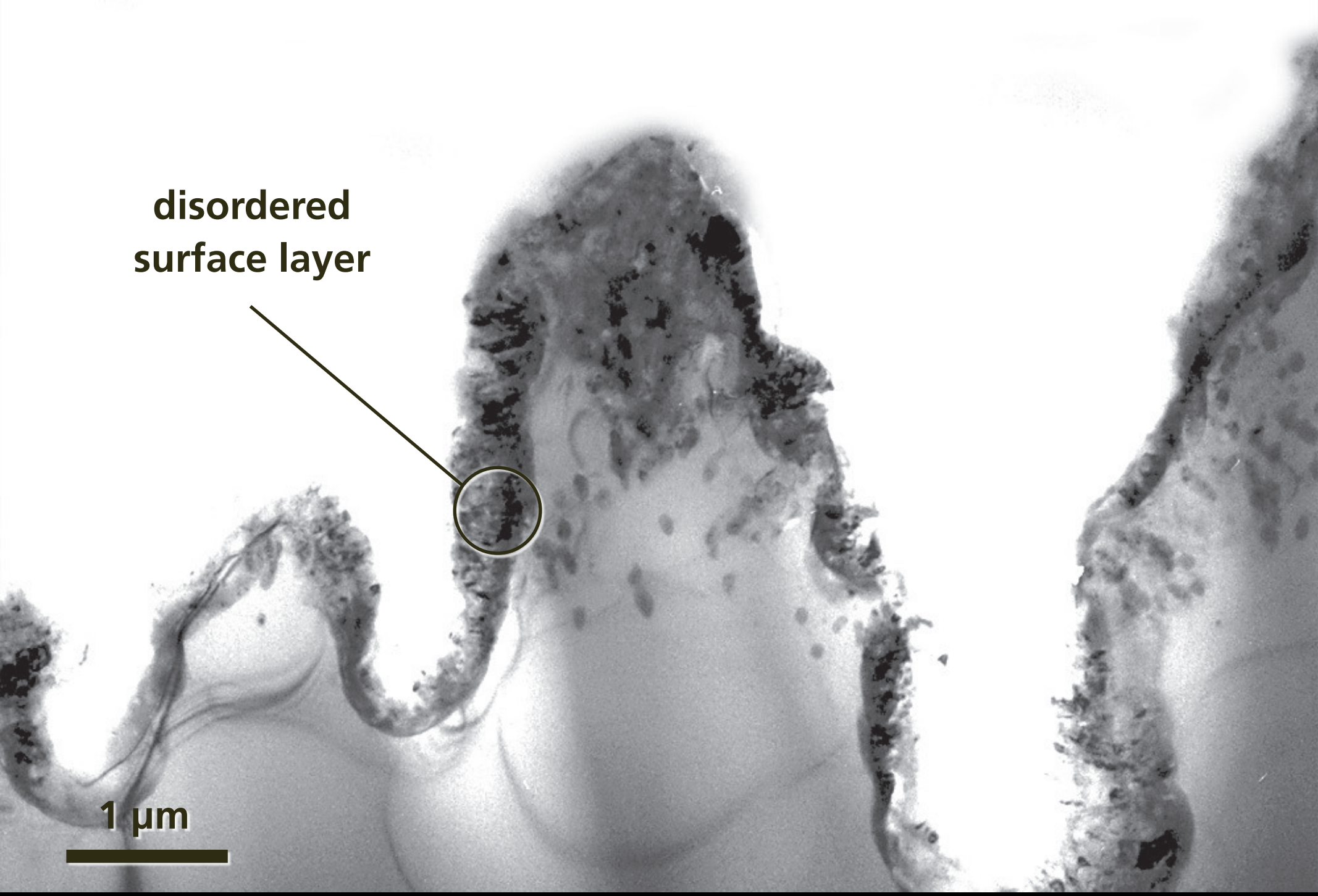
1 structure



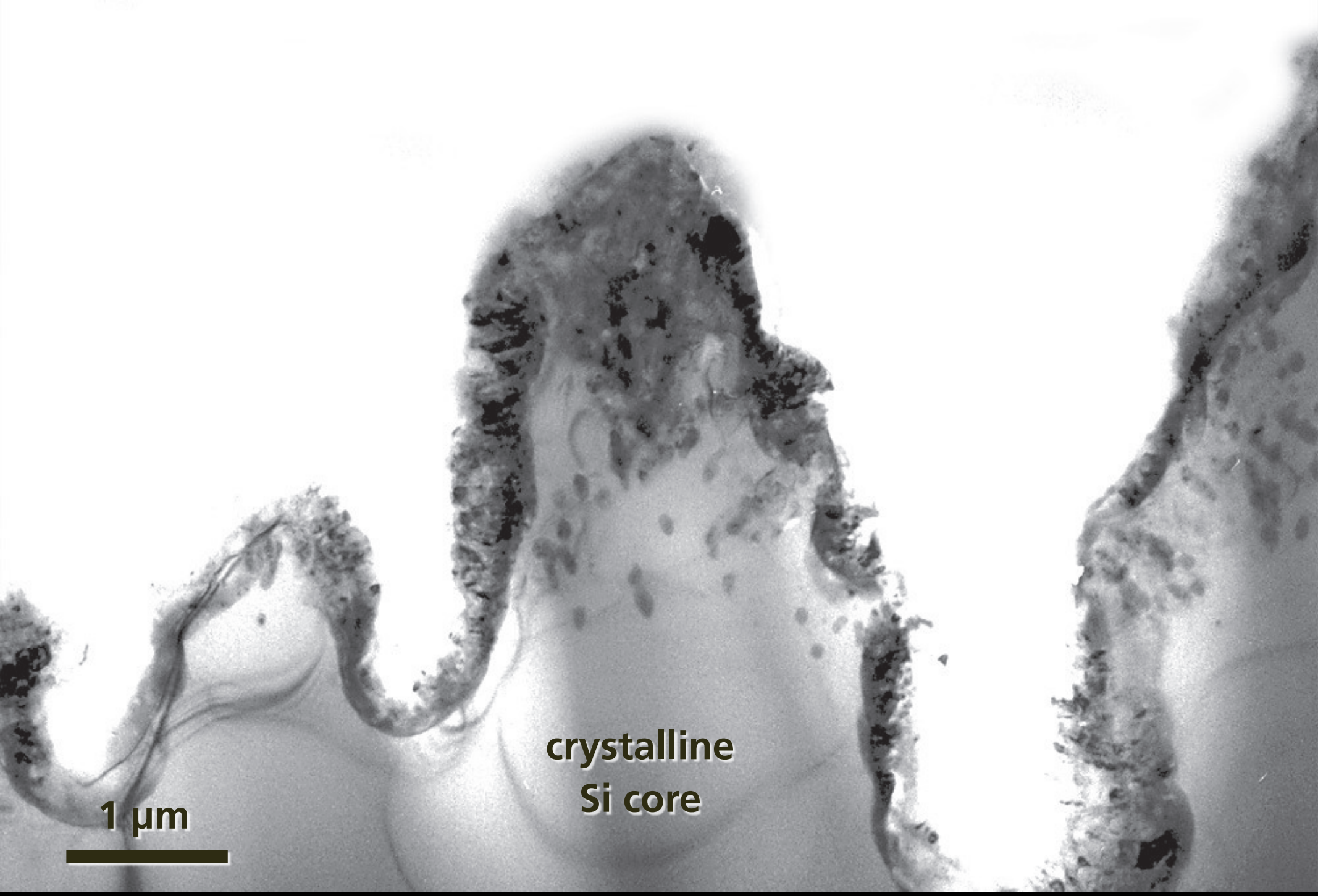
1 structure



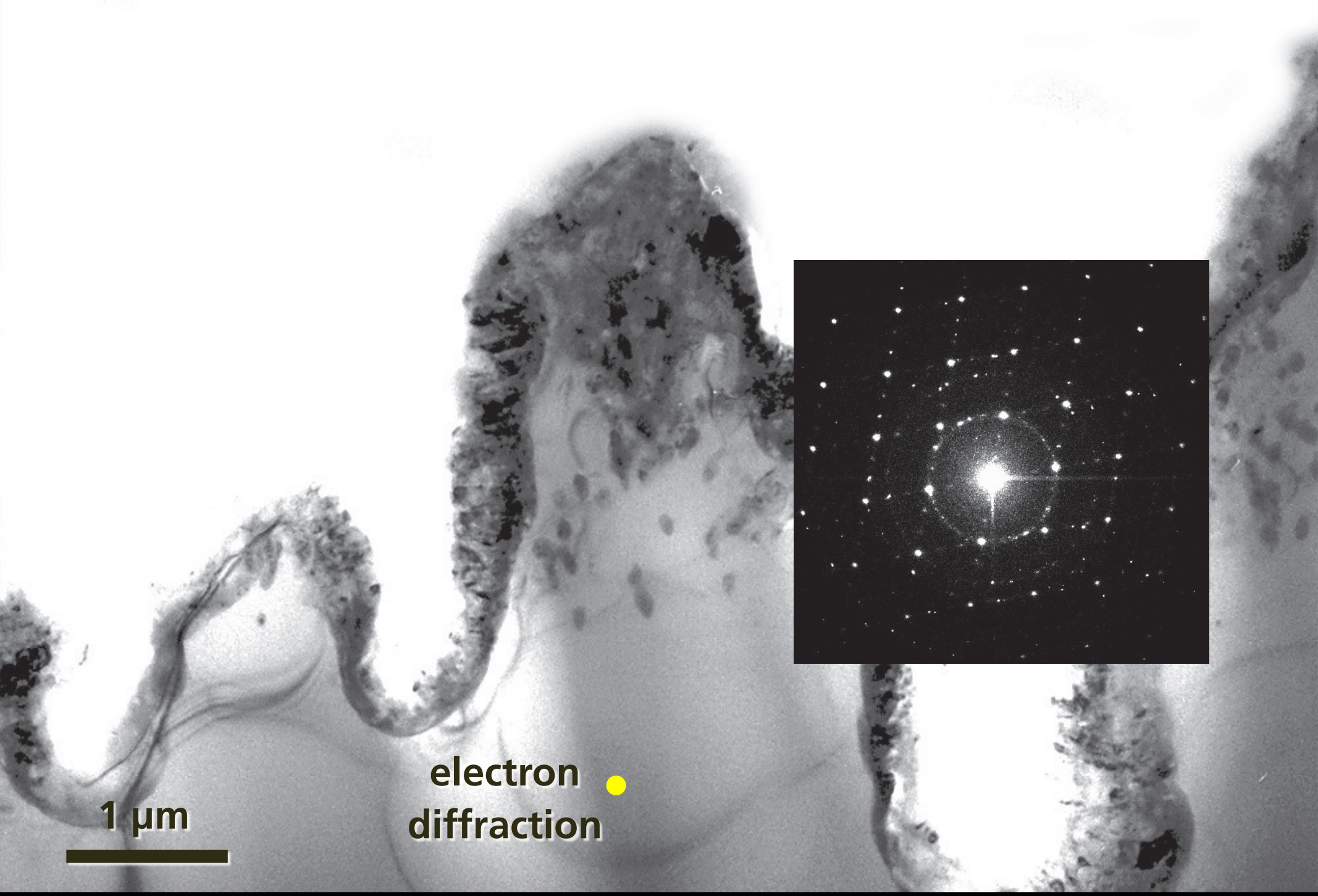
1 structure



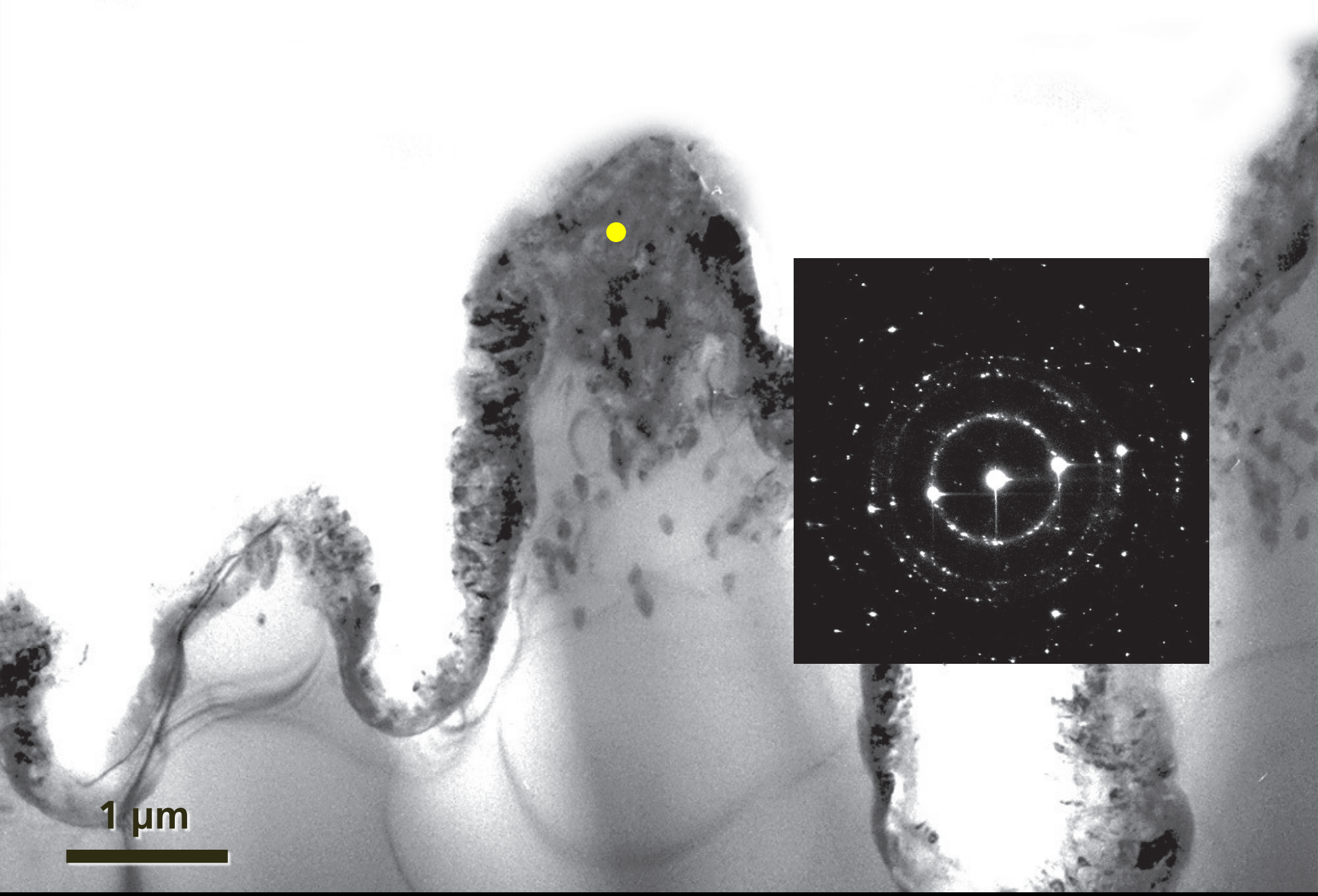
1 structure



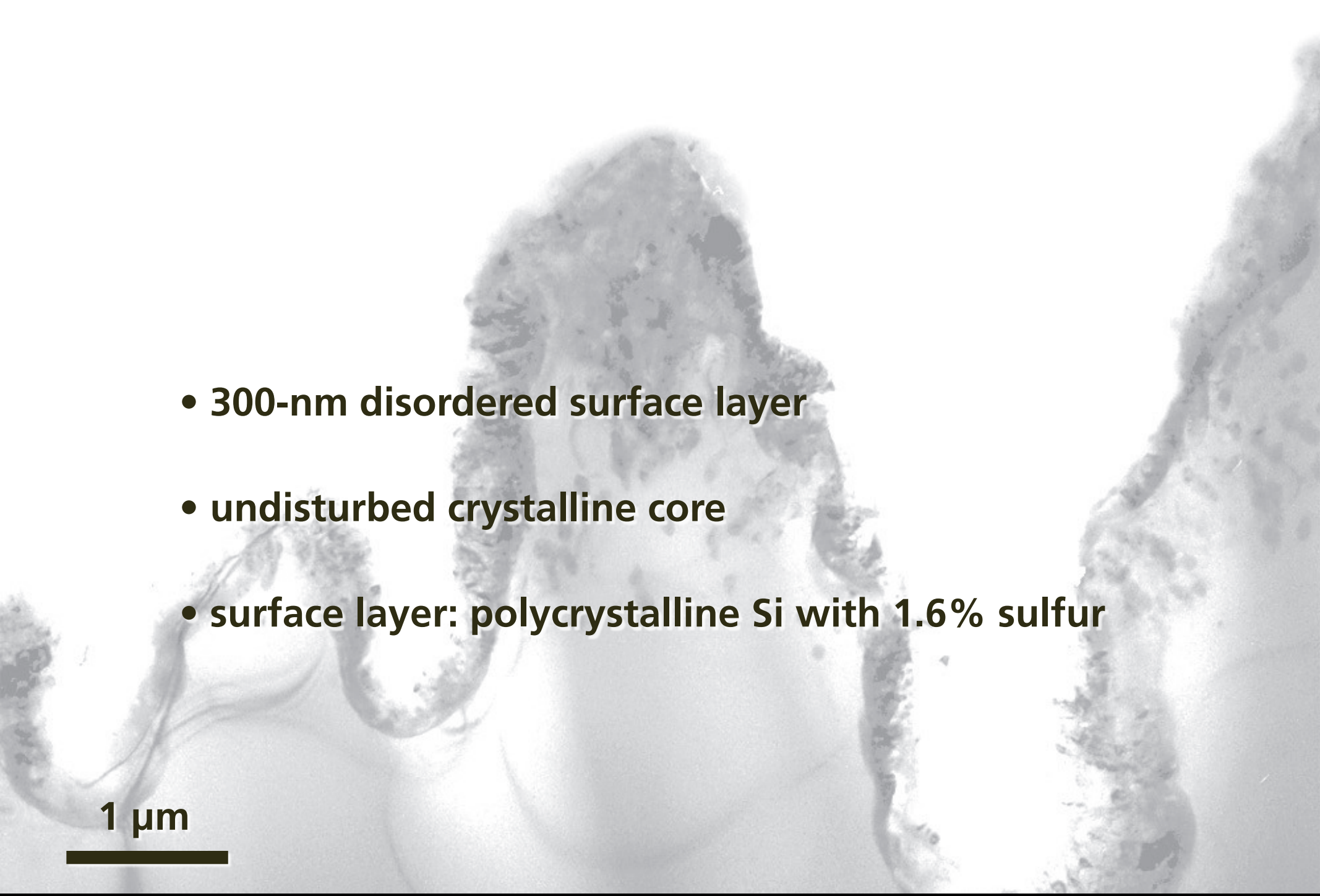
1 structure



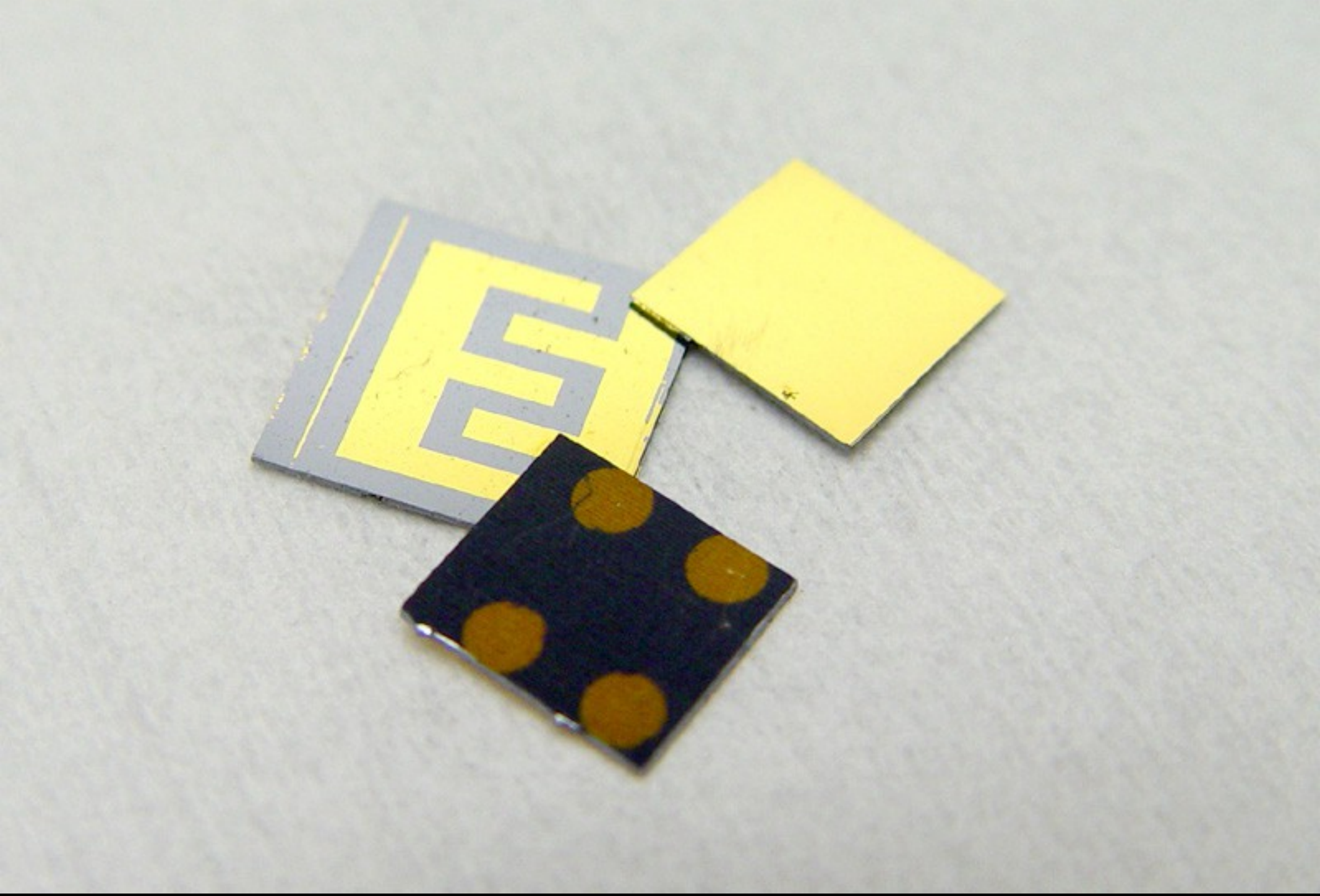
1 structure



1 structure



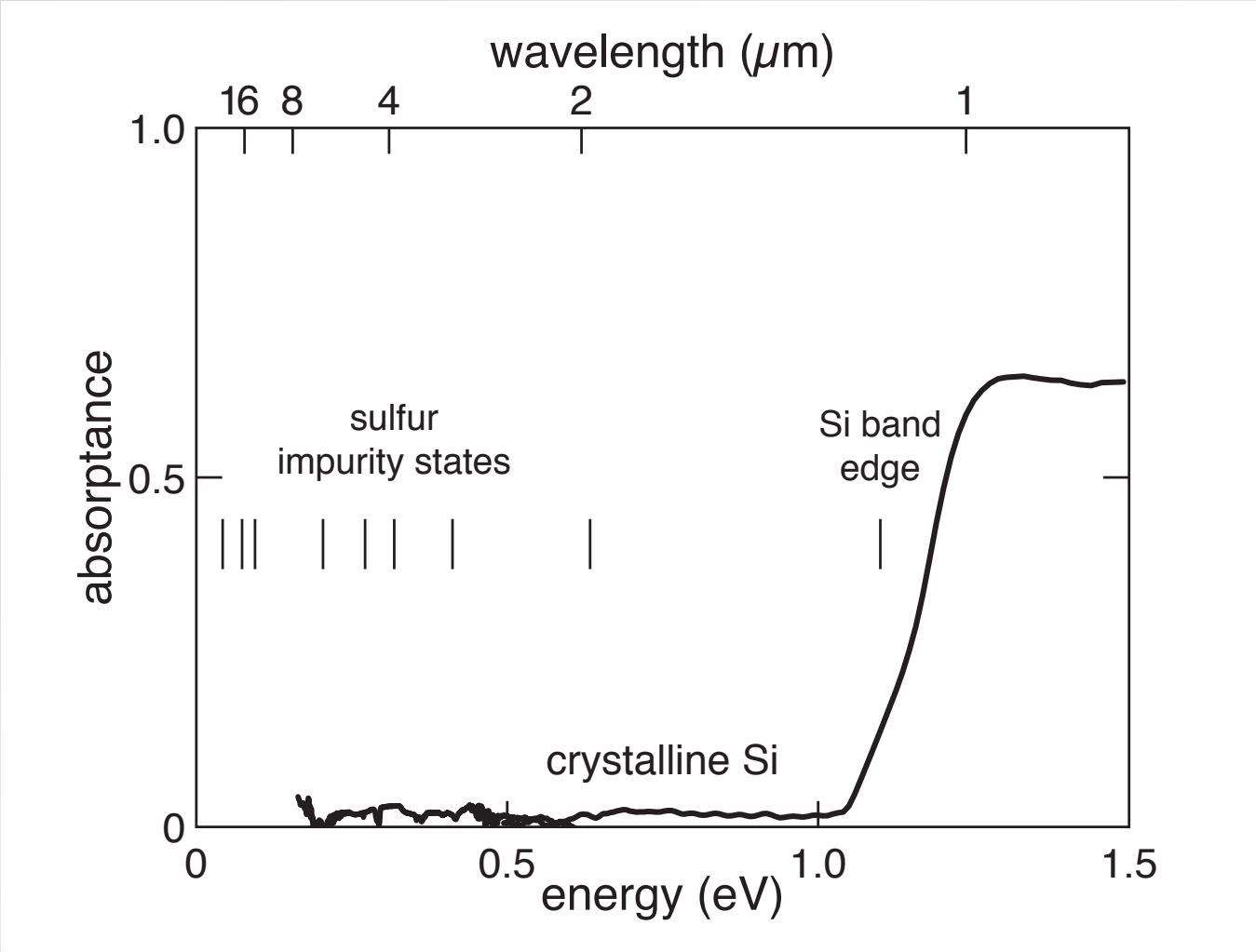
- 300-nm disordered surface layer
- undisturbed crystalline core
- surface layer: polycrystalline Si with 1.6% sulfur



1 structure

2 OE properties

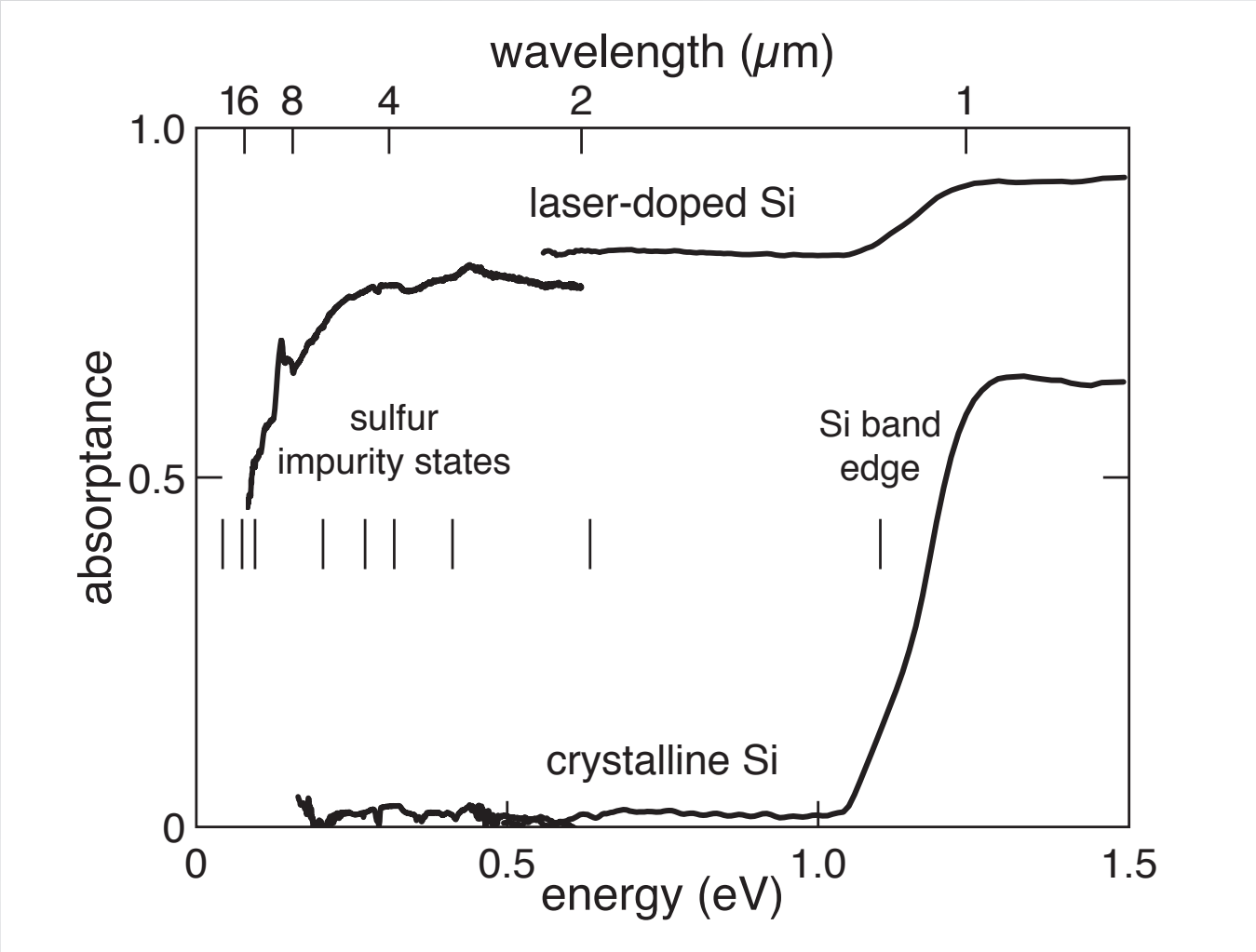
10^{-6} sulfur doping



1 structure

2 OE properties

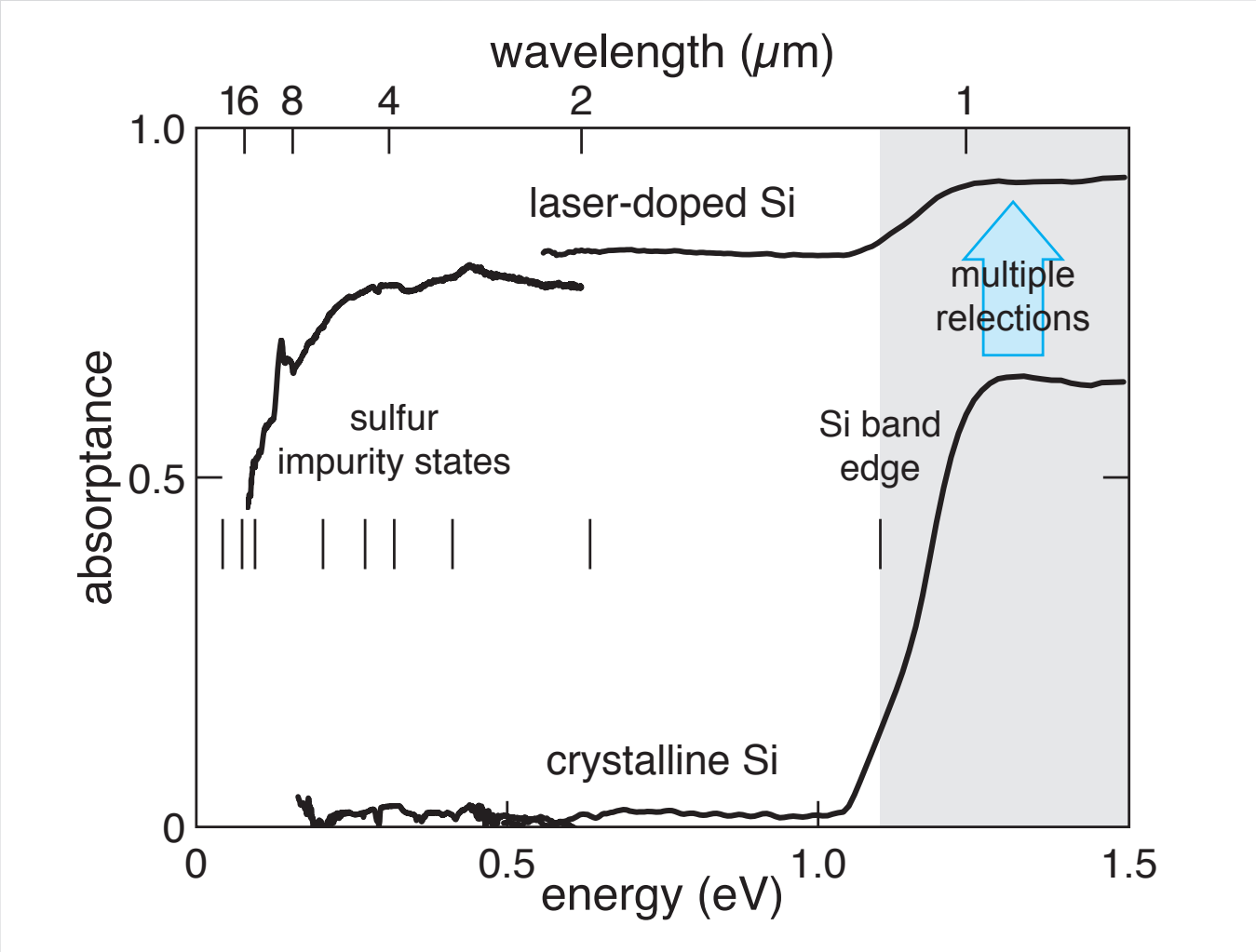
laser-doped S:Si



1 structure

2 OE properties

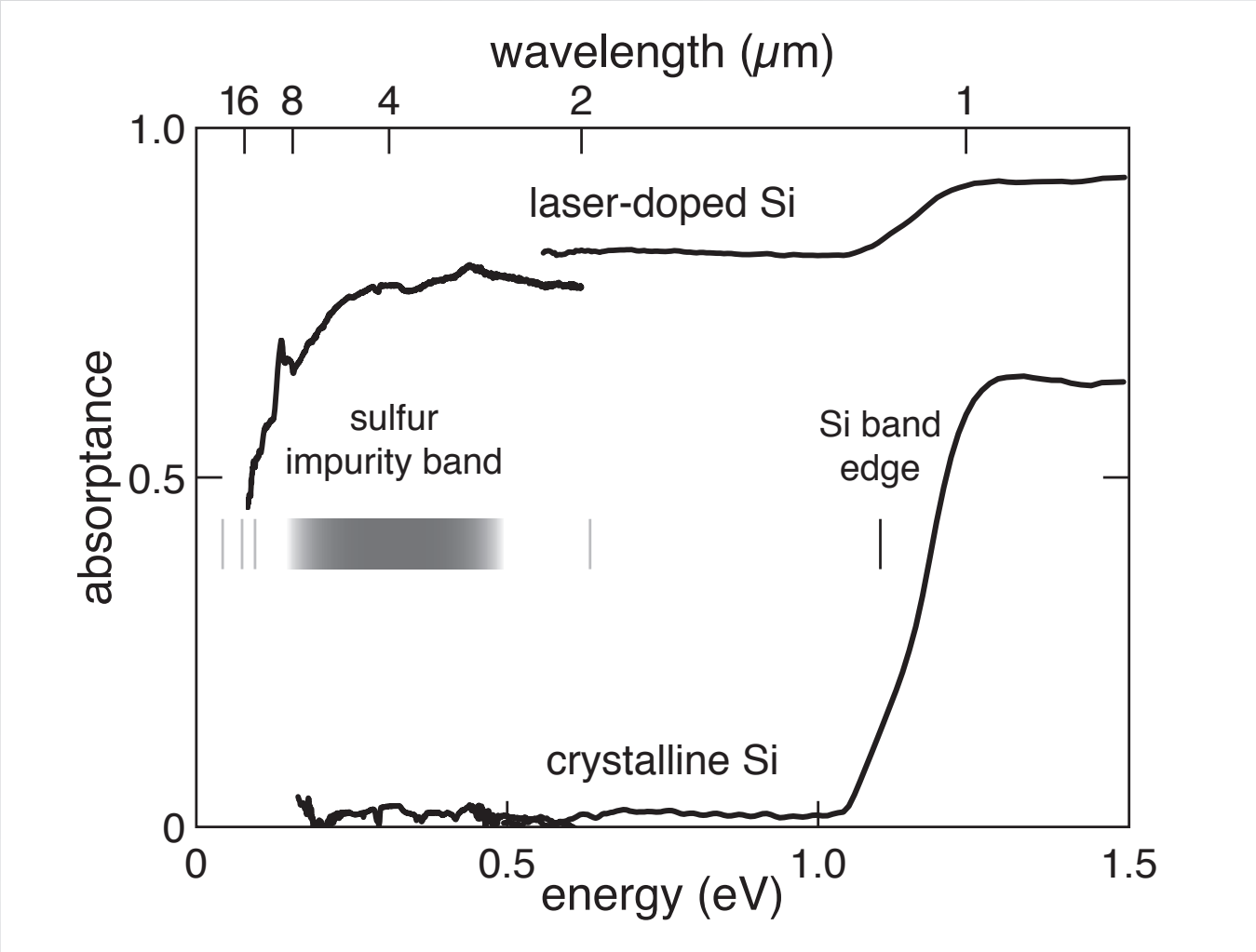
laser-doped S:Si



1 structure

2 OE properties

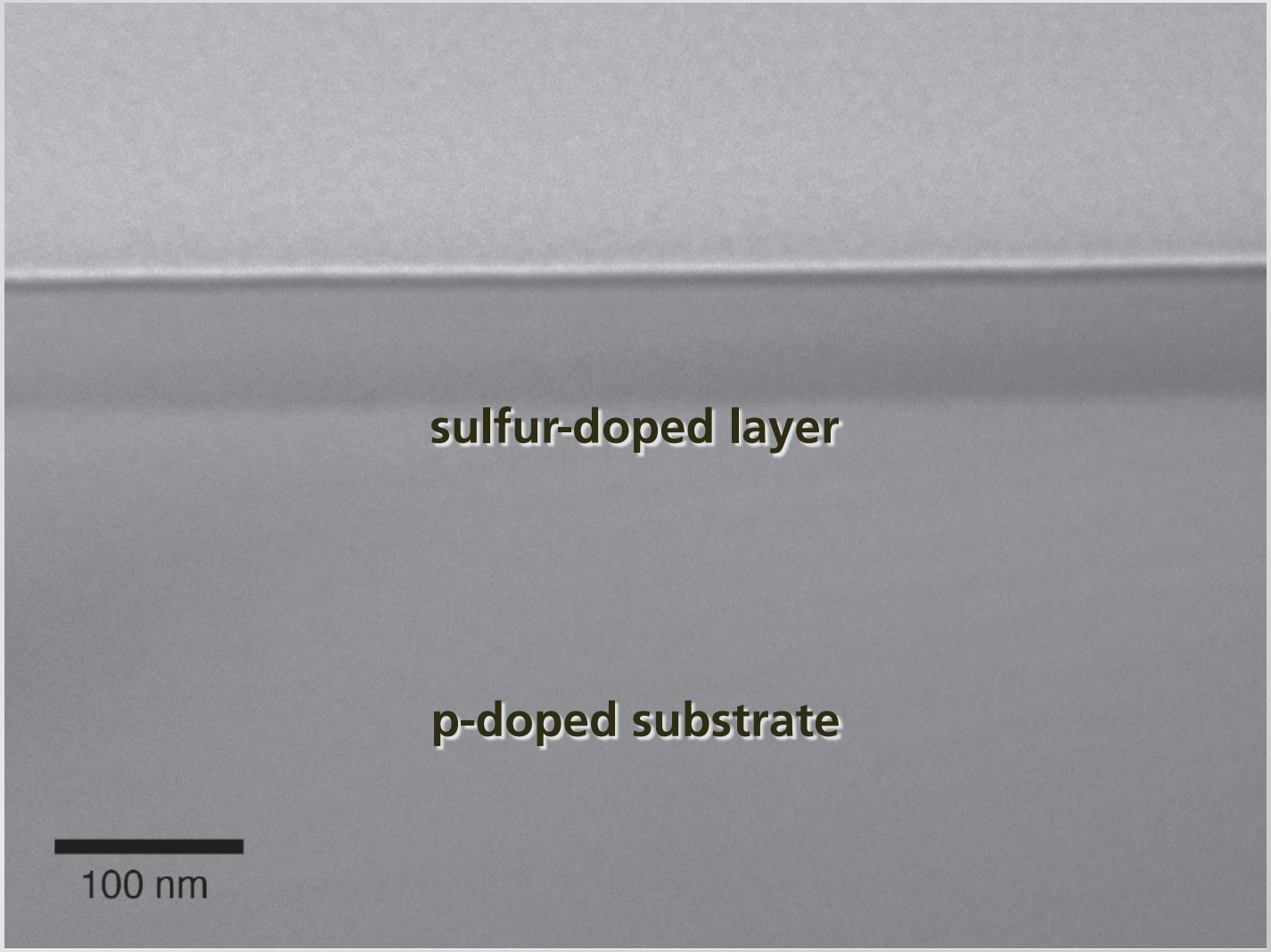
laser-doped S:Si



1 structure

2 OE properties

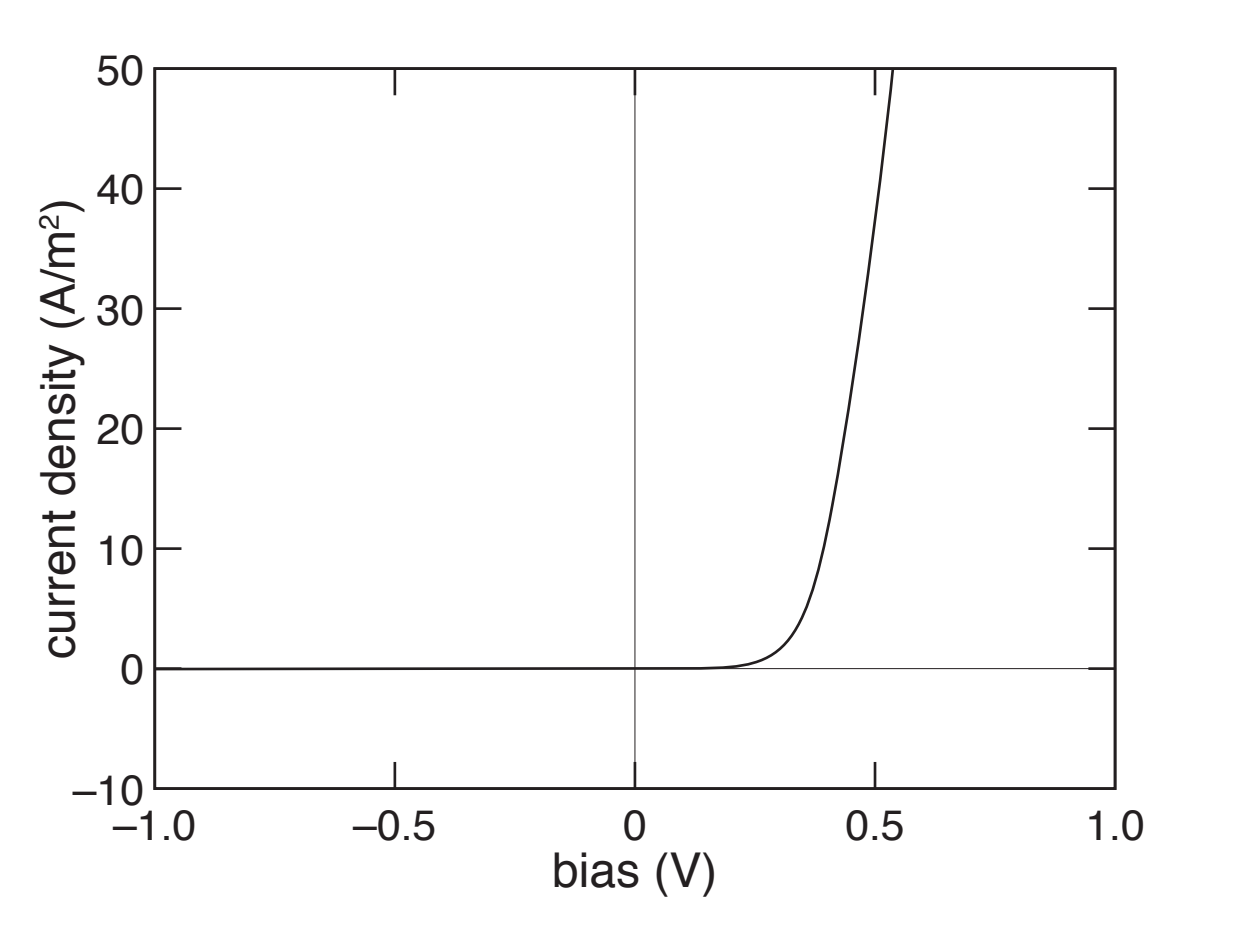
should have shallow junction below surface



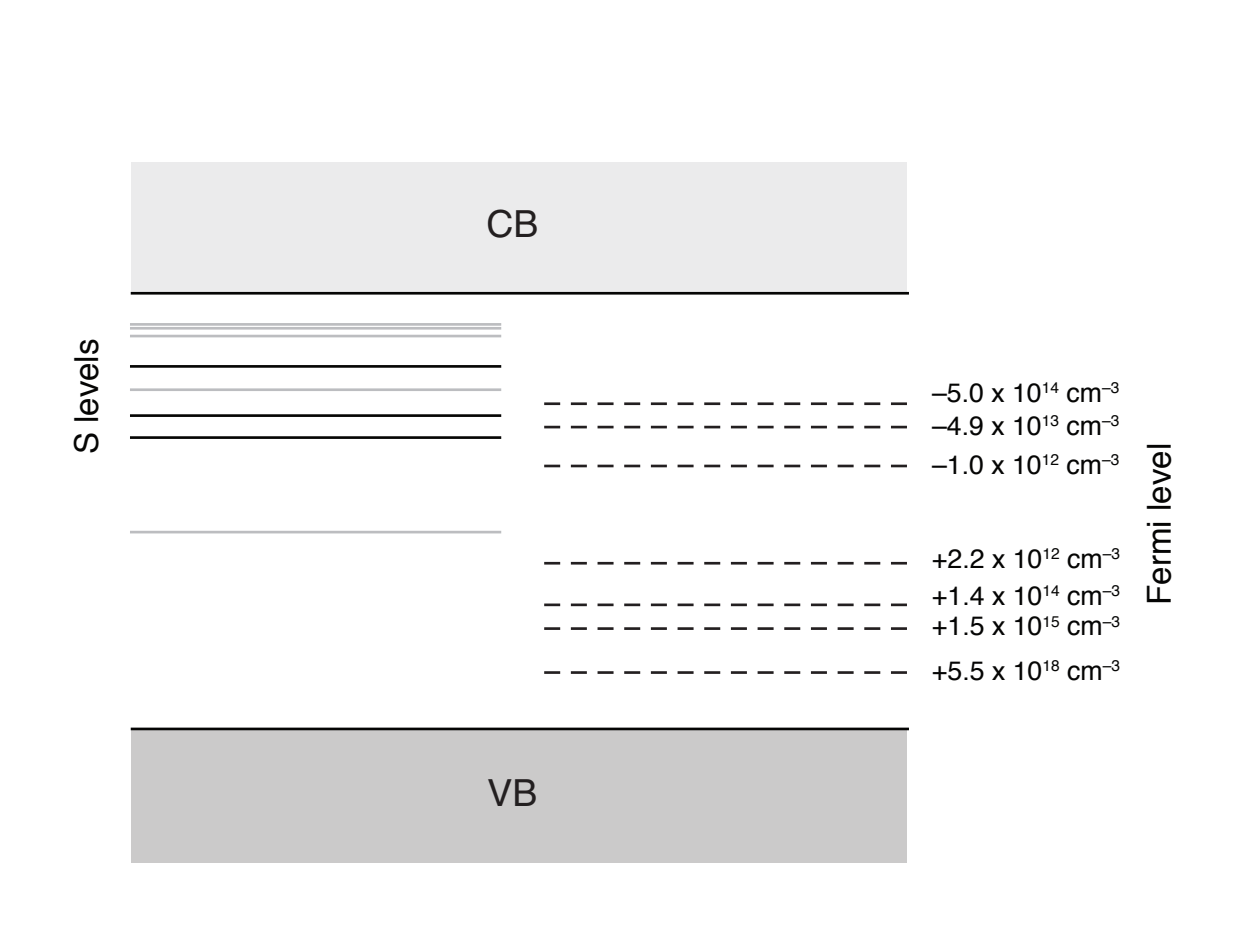
1 structure

2 OE properties

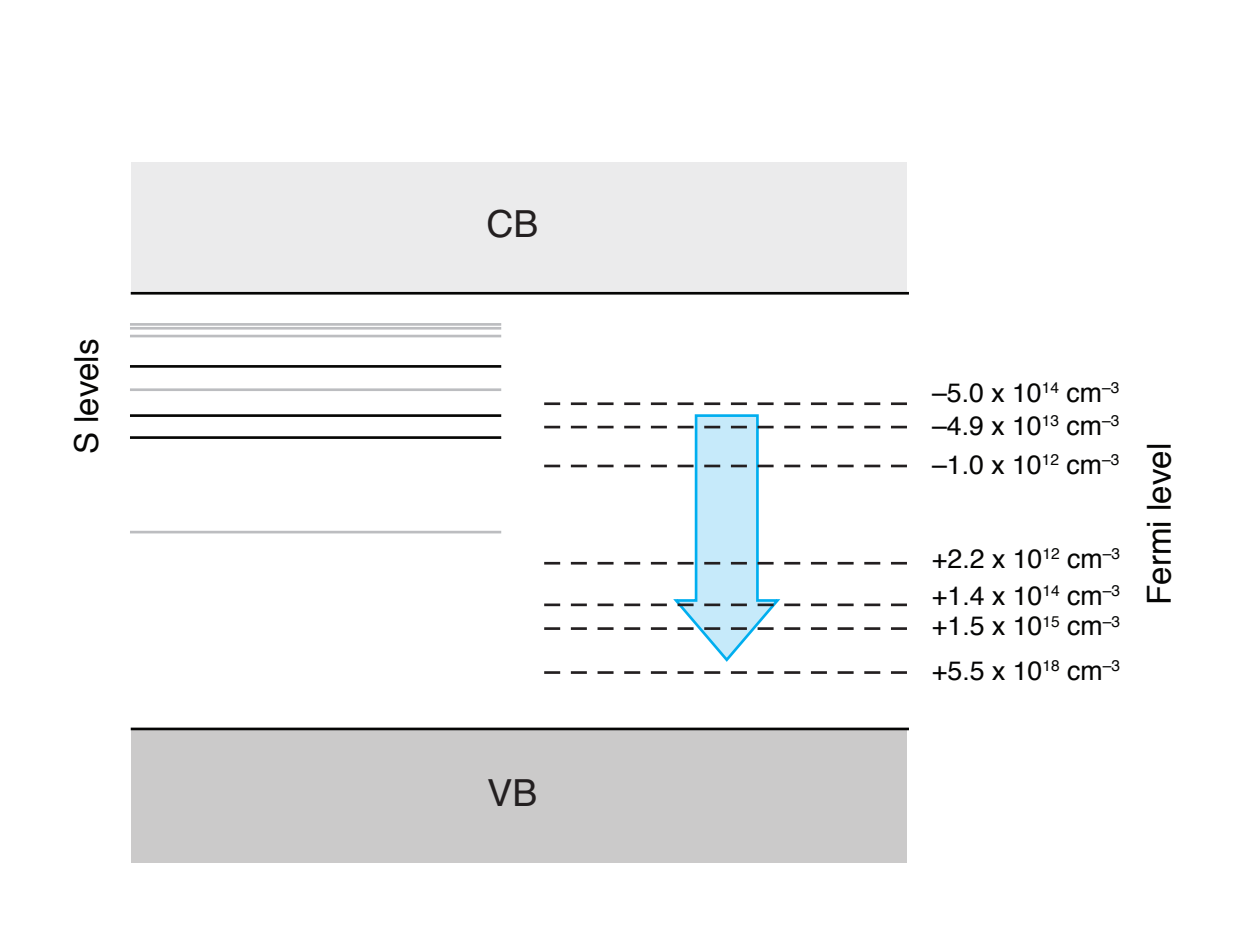
excellent rectification (after annealing)



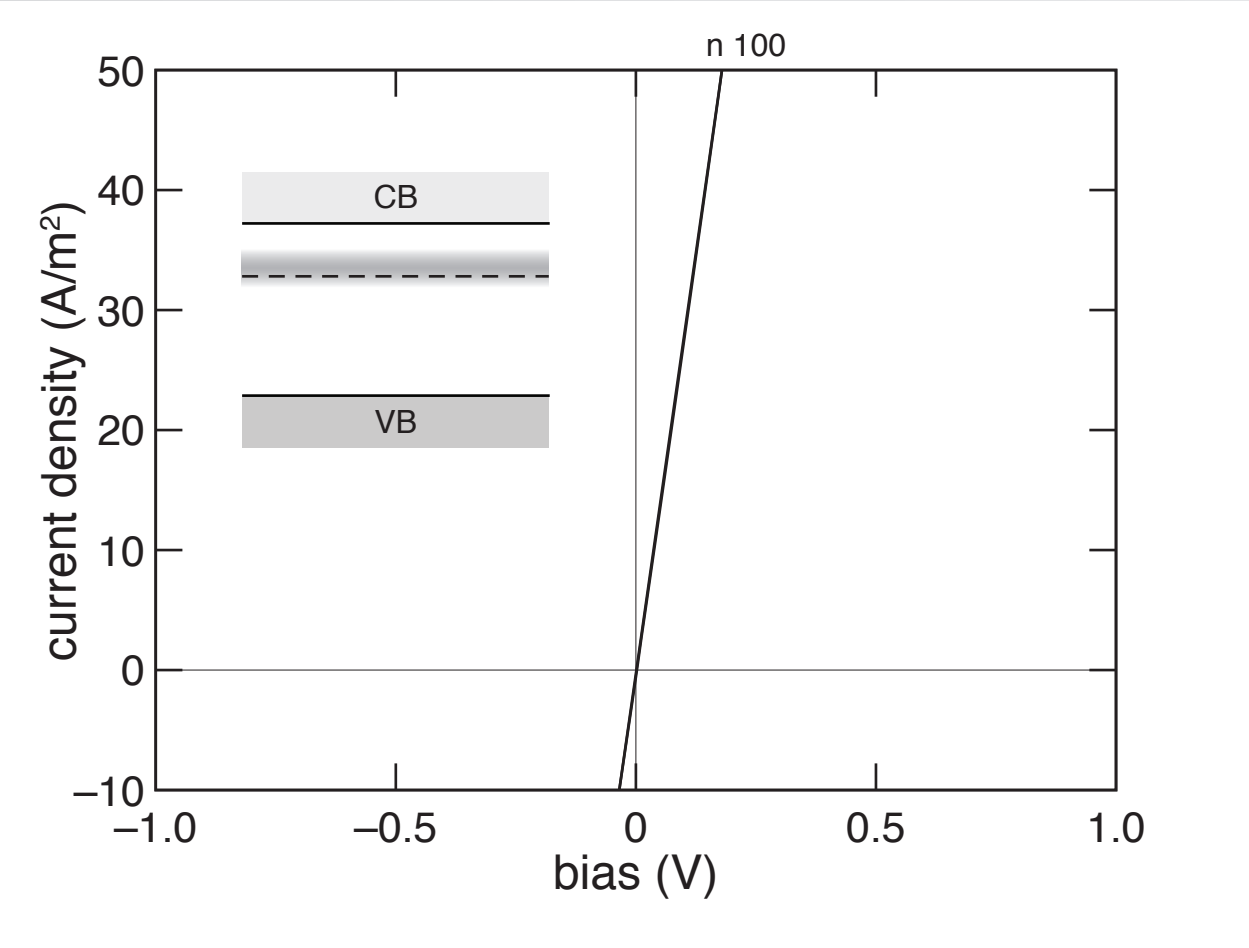
probe impurity states by varying Fermi level in substrate



probe impurity states by varying Fermi level in substrate



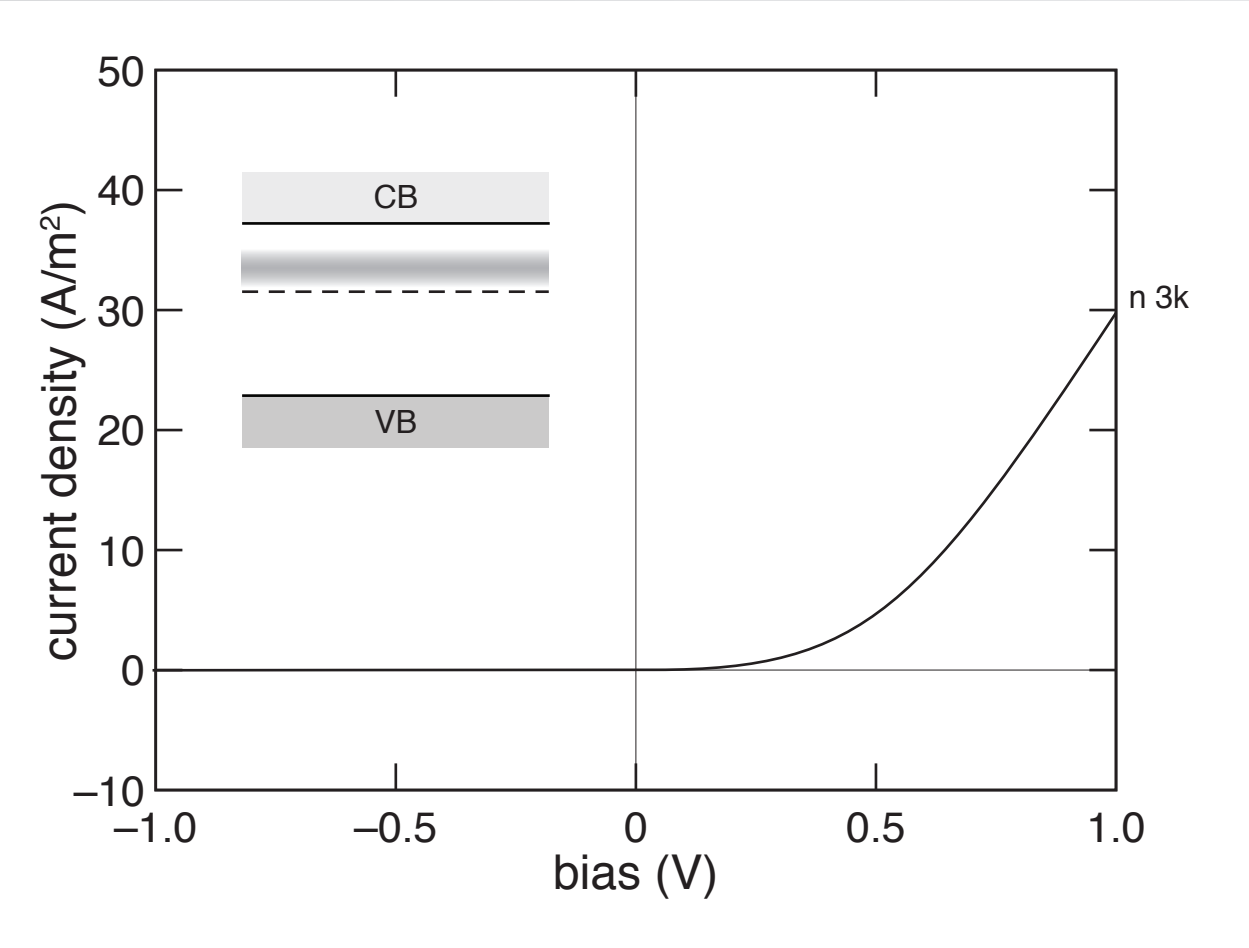
vary substrate doping type and resistivity



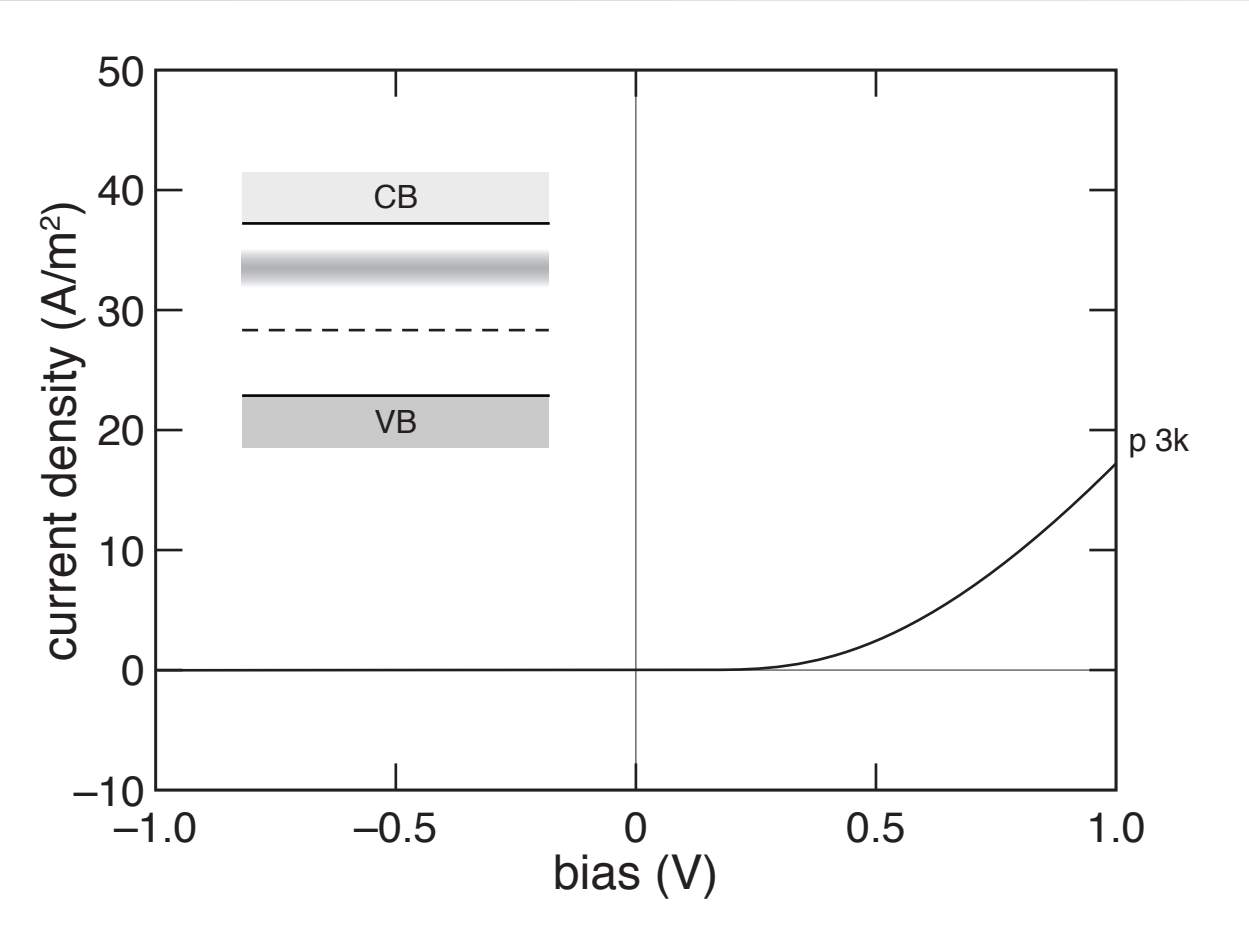
1 structure

2 OE properties

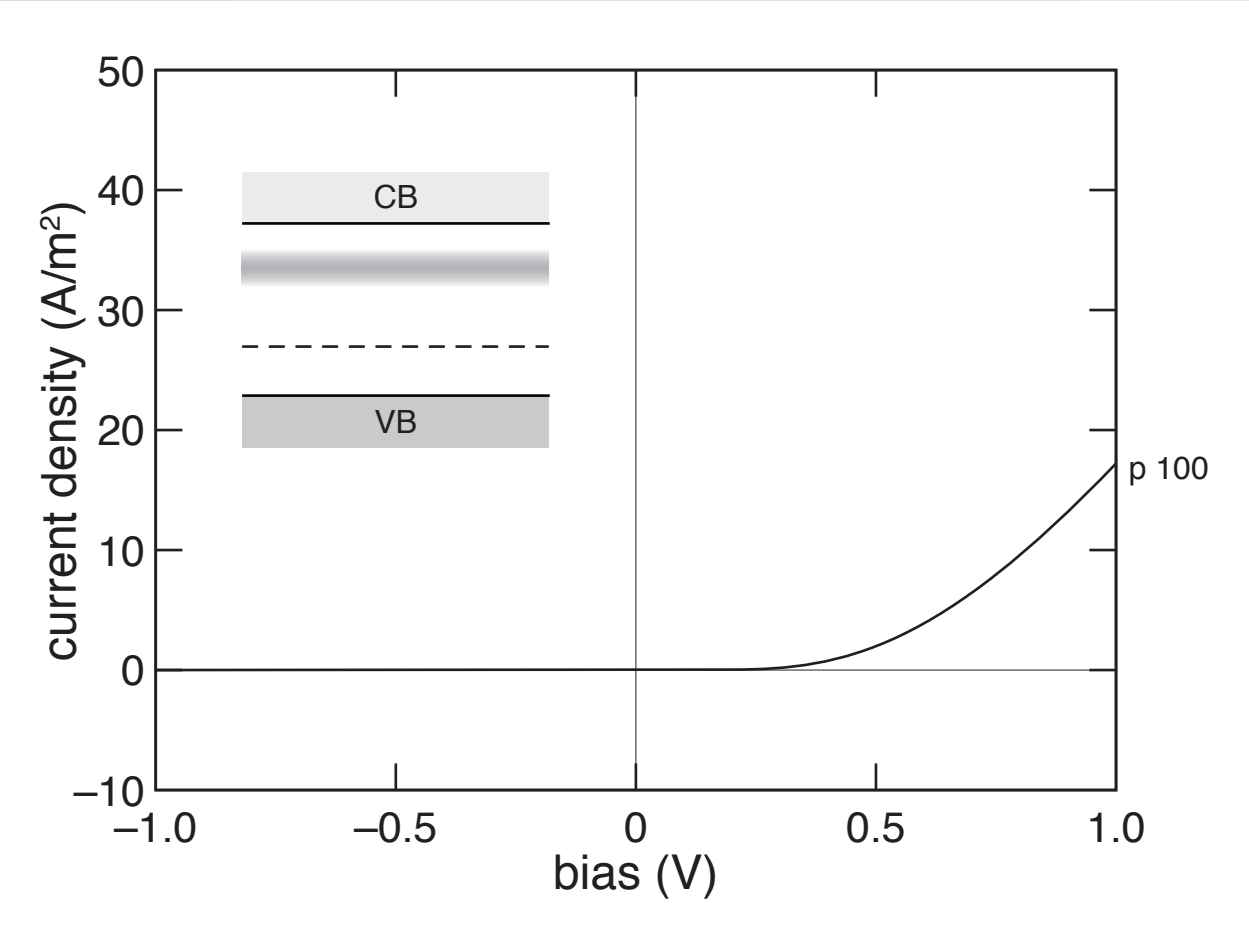
vary substrate doping type and resistivity



vary substrate doping type and resistivity



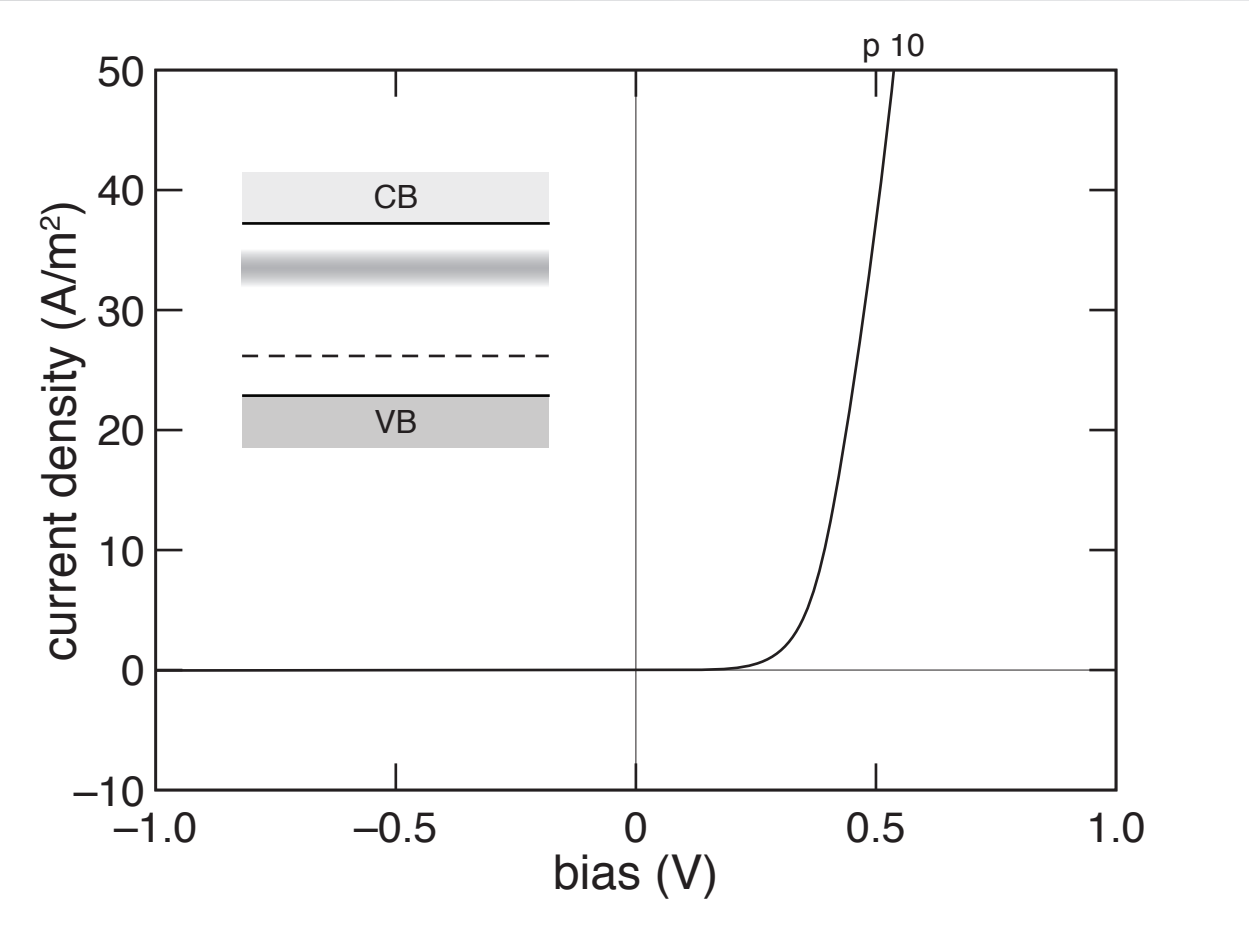
vary substrate doping type and resistivity



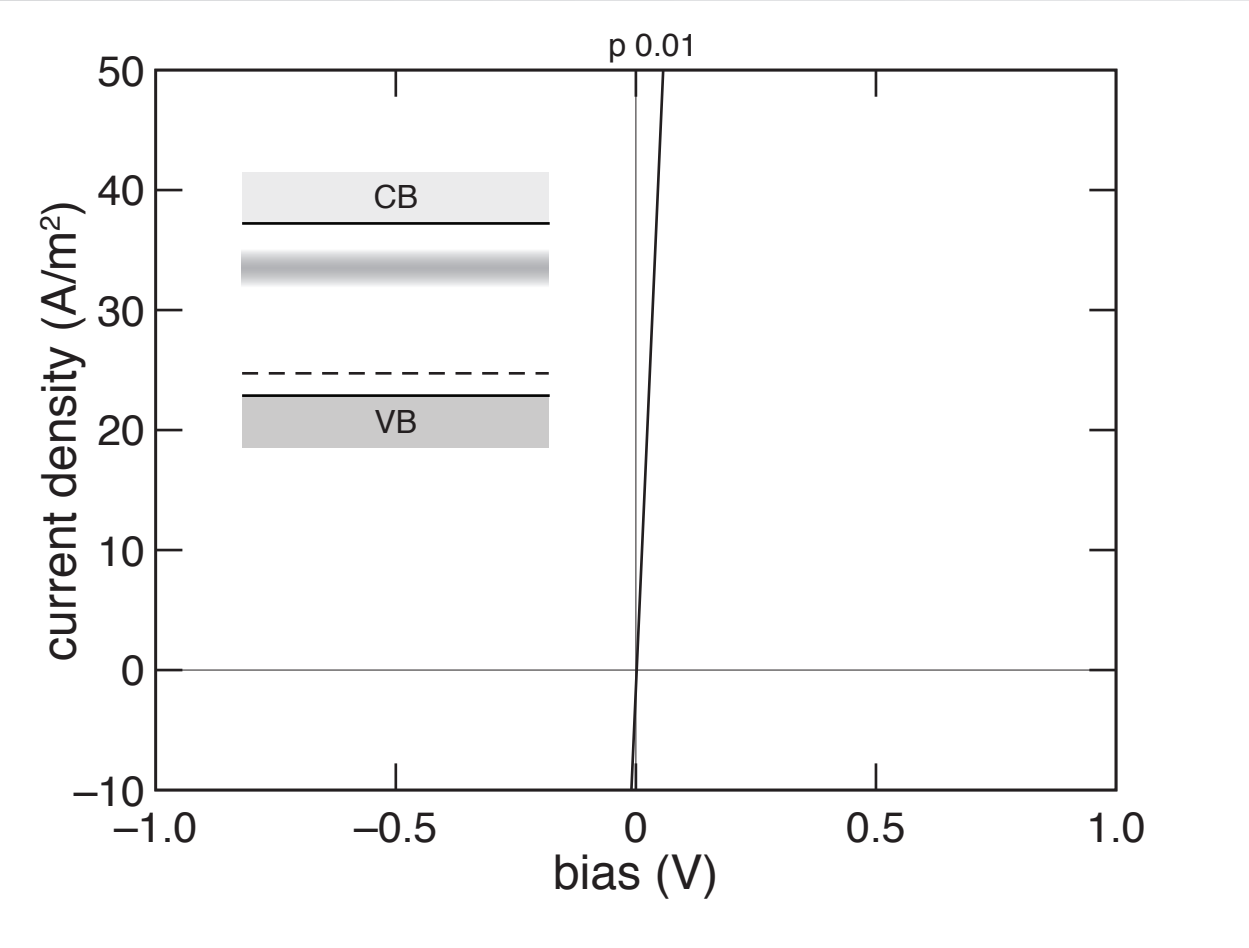
1 structure

2 OE properties

vary substrate doping type and resistivity



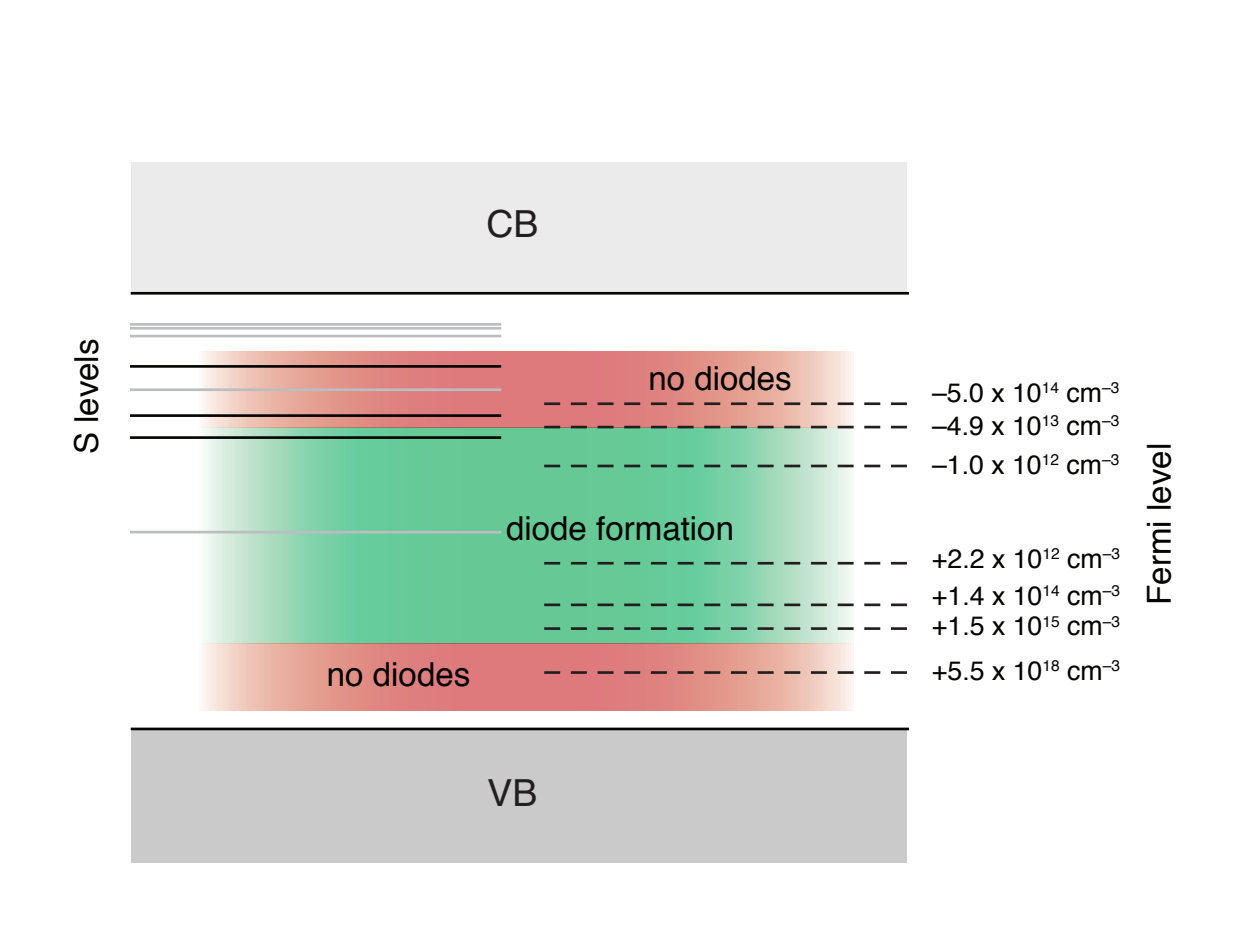
vary substrate doping type and resistivity



1 structure

2 OE properties

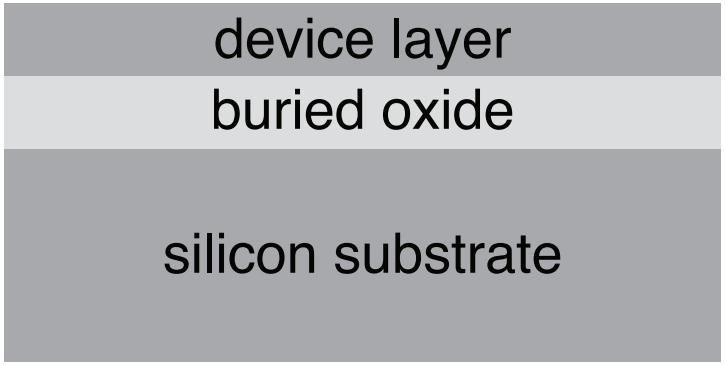
probe impurity states by varying Fermi level in substrate



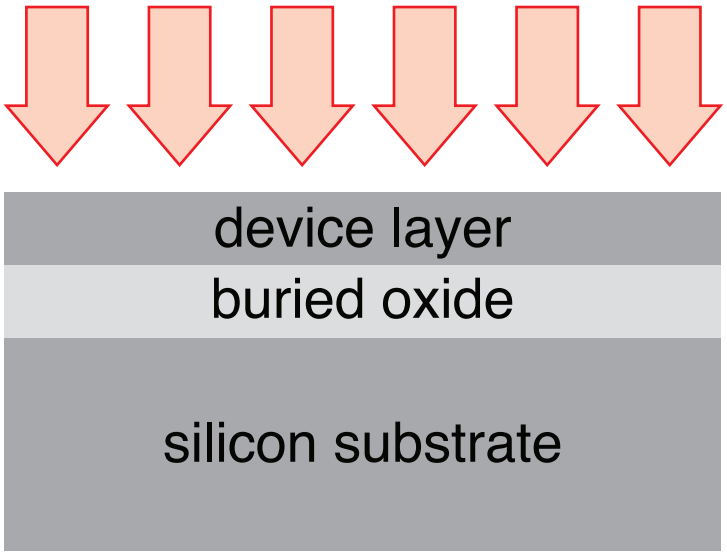
IV behavior consistent with

impurity band between 200 and 400 meV

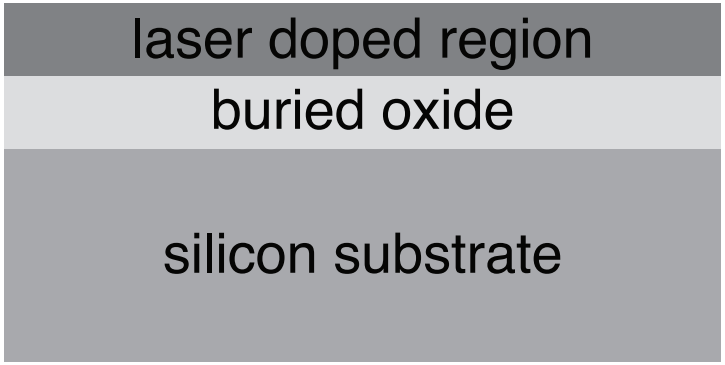
isolate surface layer for Hall measurements



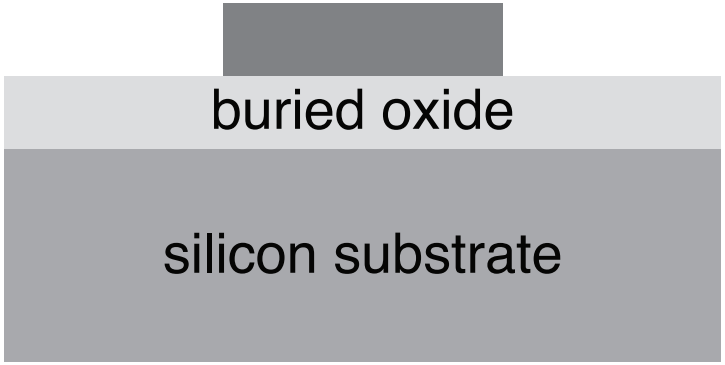
isolate surface layer for Hall measurements



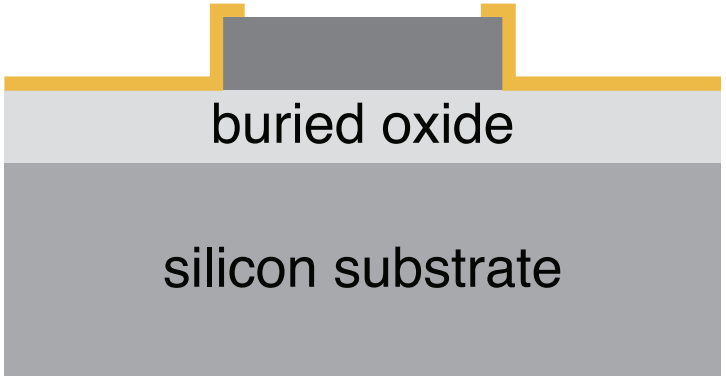
isolate surface layer for Hall measurements

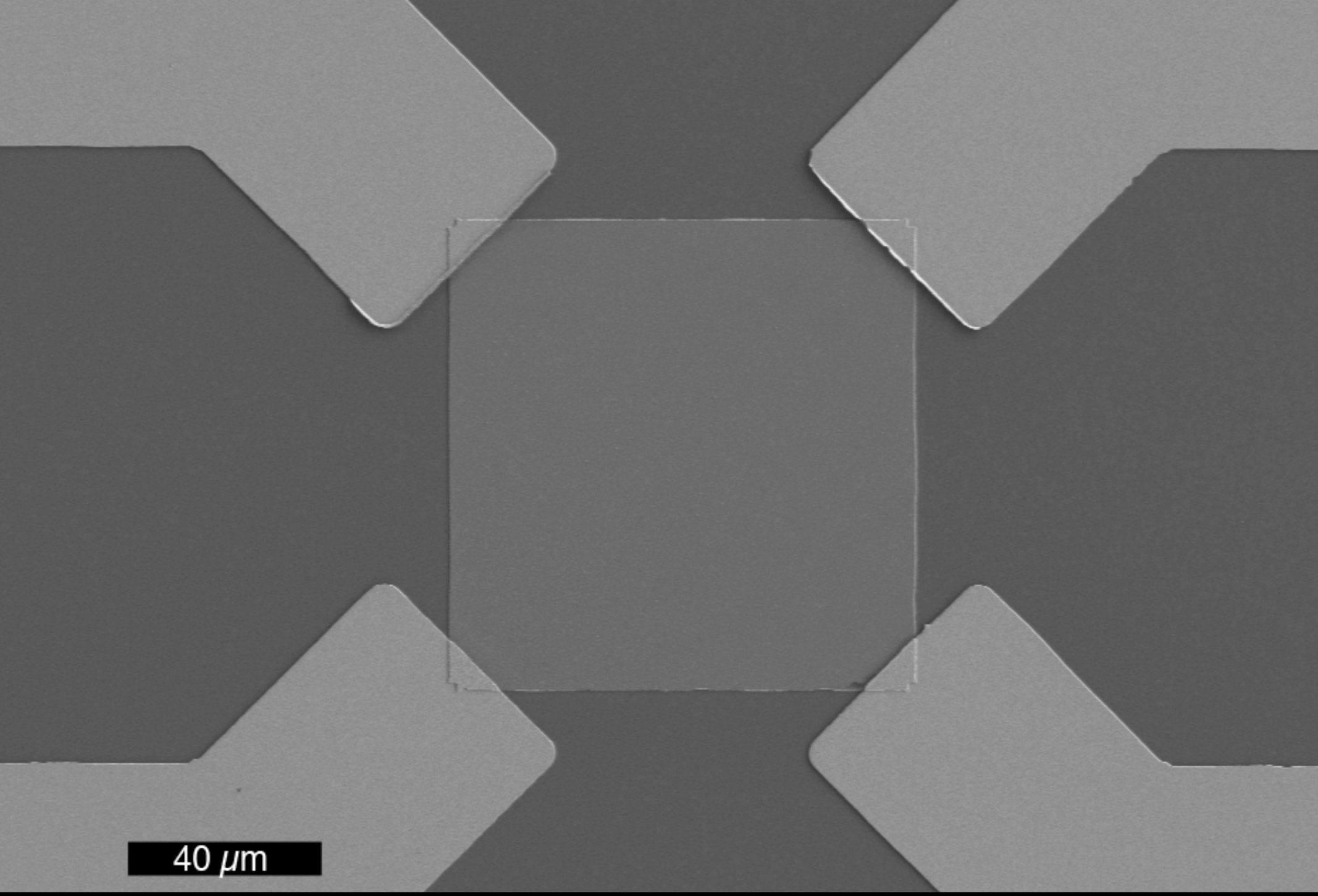


isolate surface layer for Hall measurements



isolate surface layer for Hall measurements

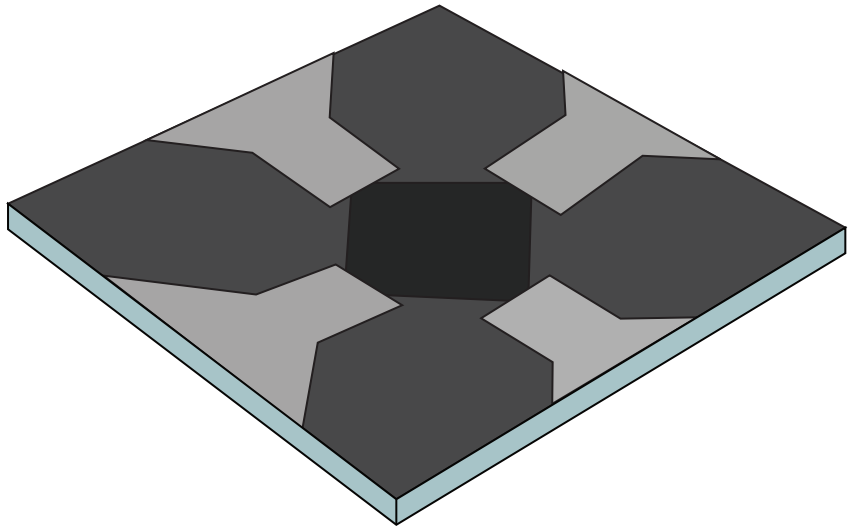




1 structure

2 OE properties

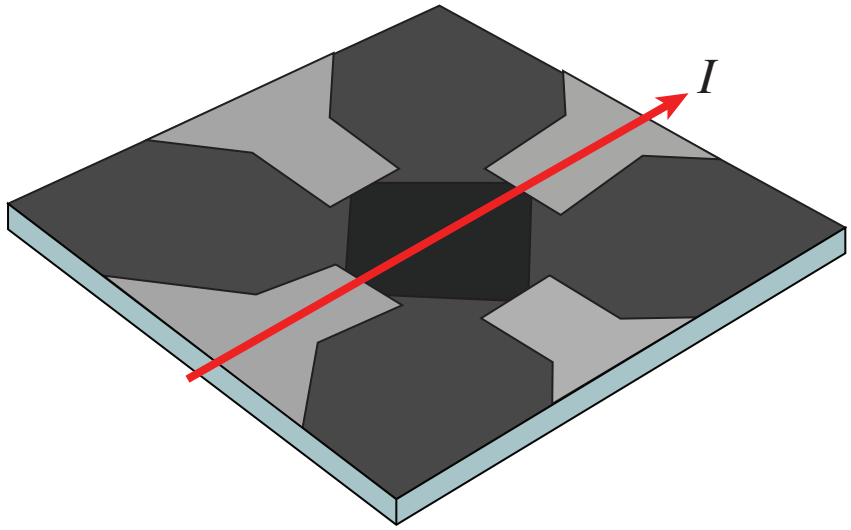
Hall measurements



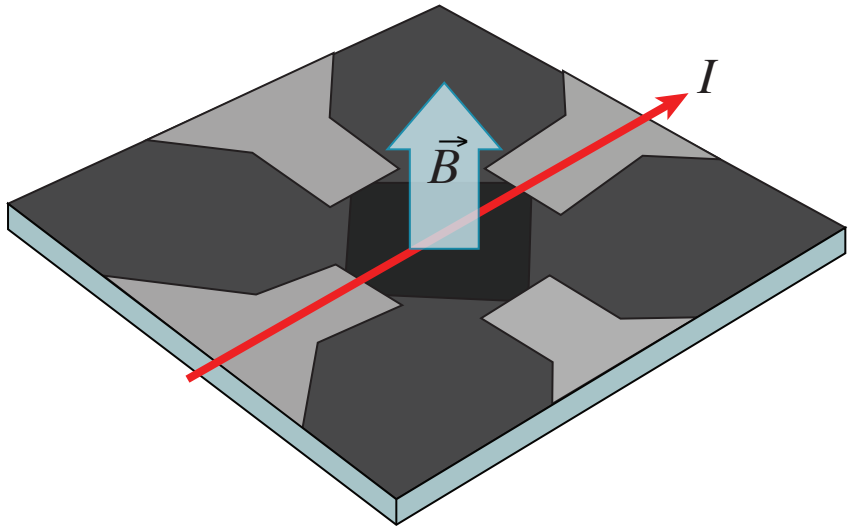
1 structure

2 OE properties

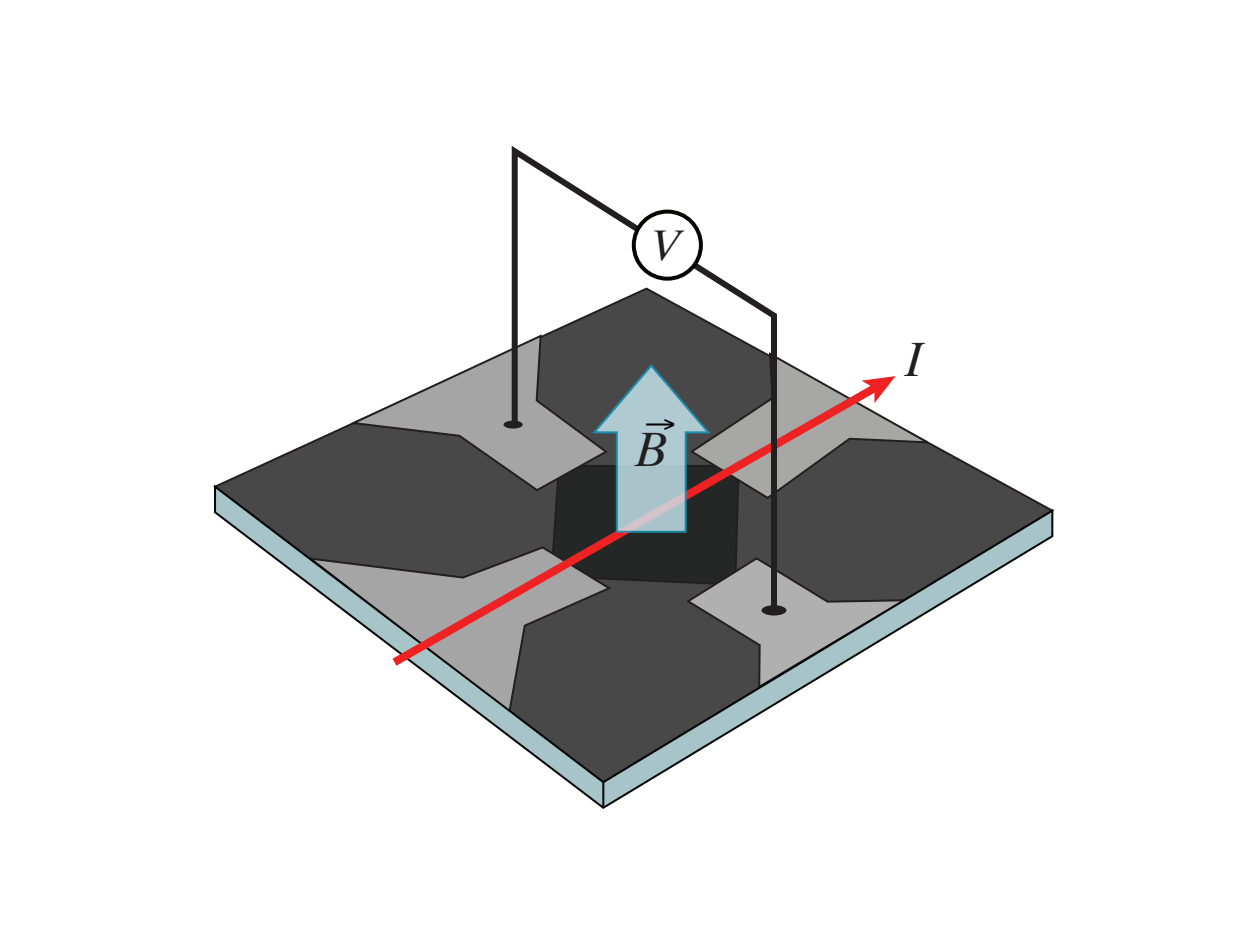
Hall measurements



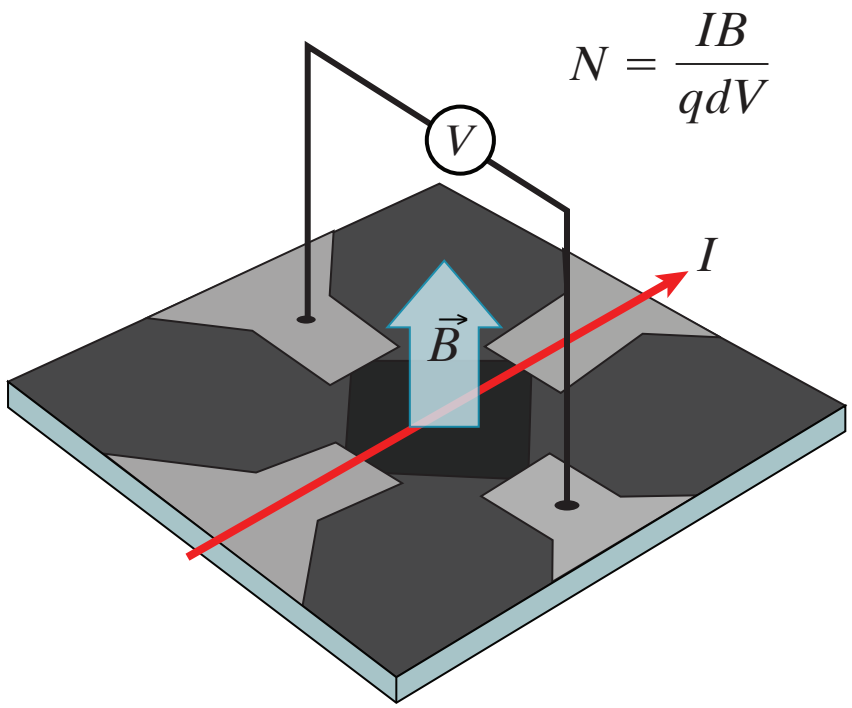
Hall measurements



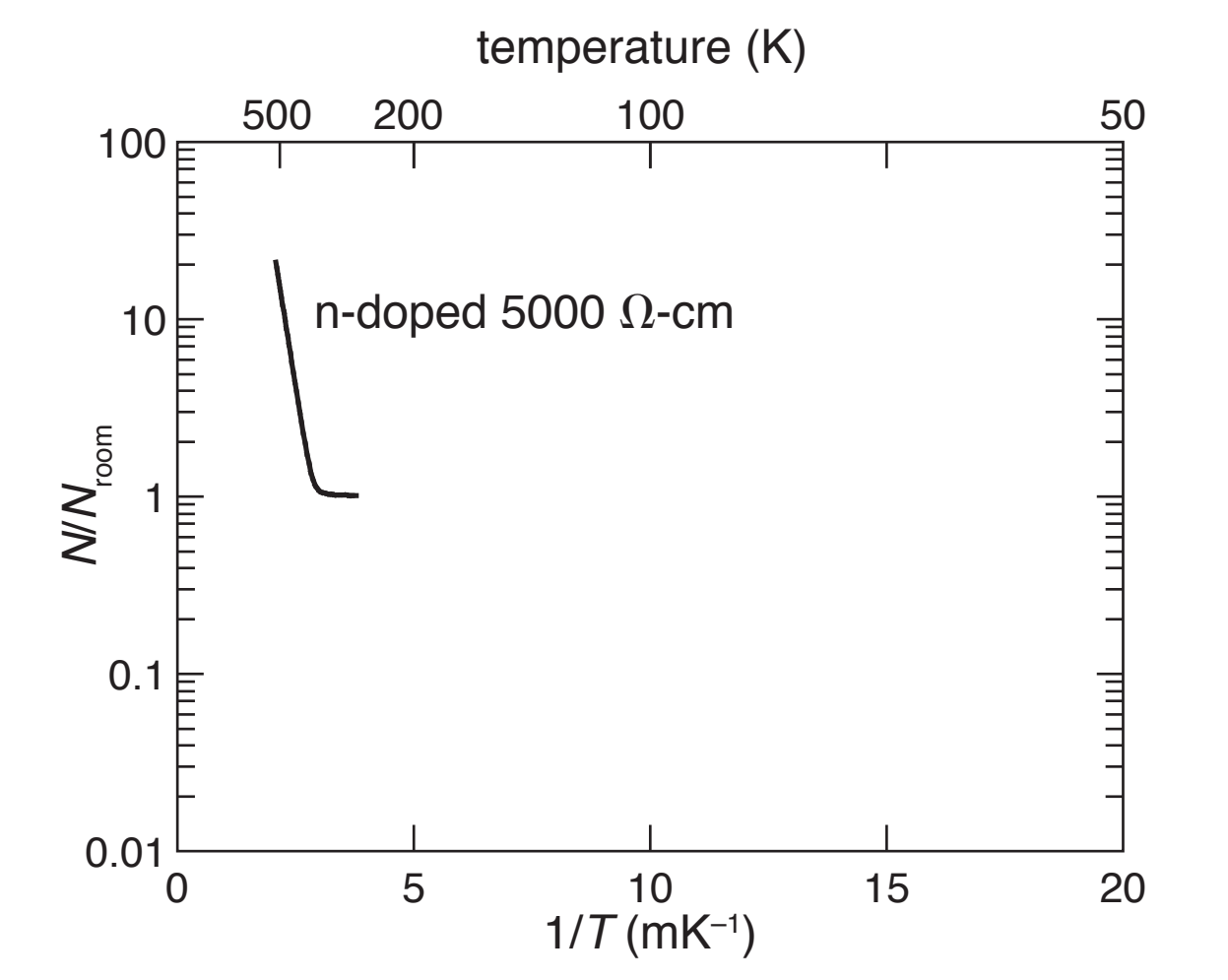
Hall measurements



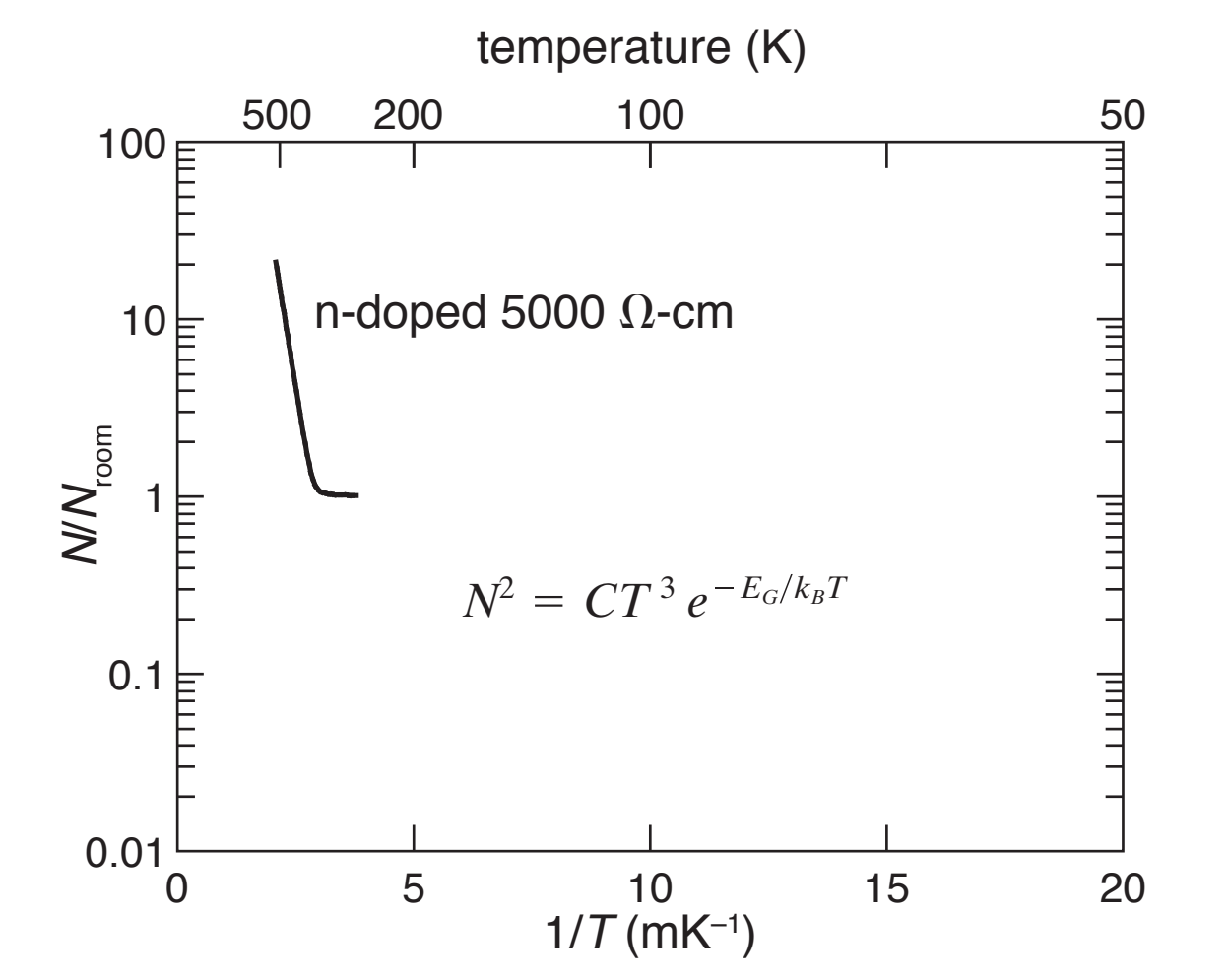
Hall measurements



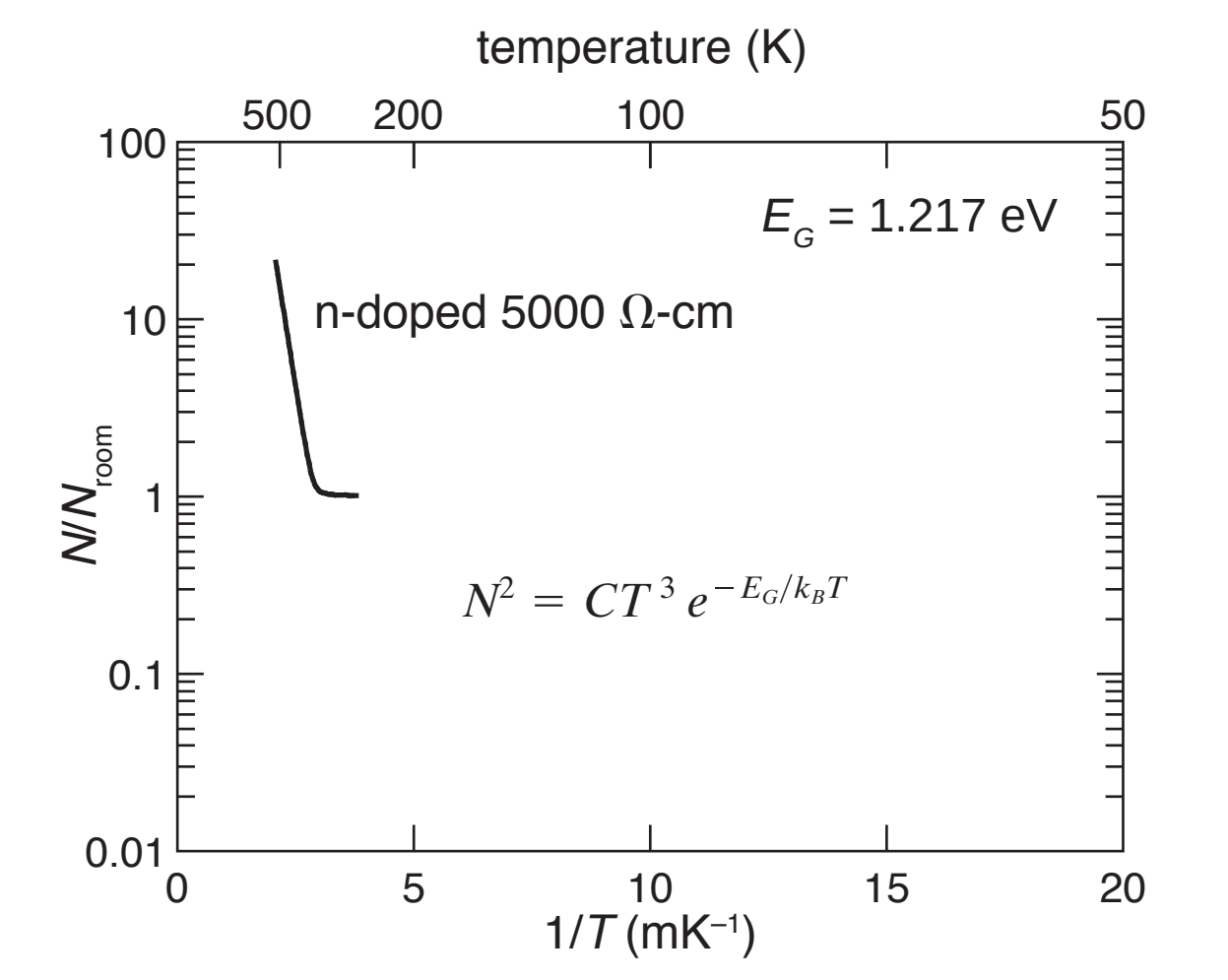
Hall measurements



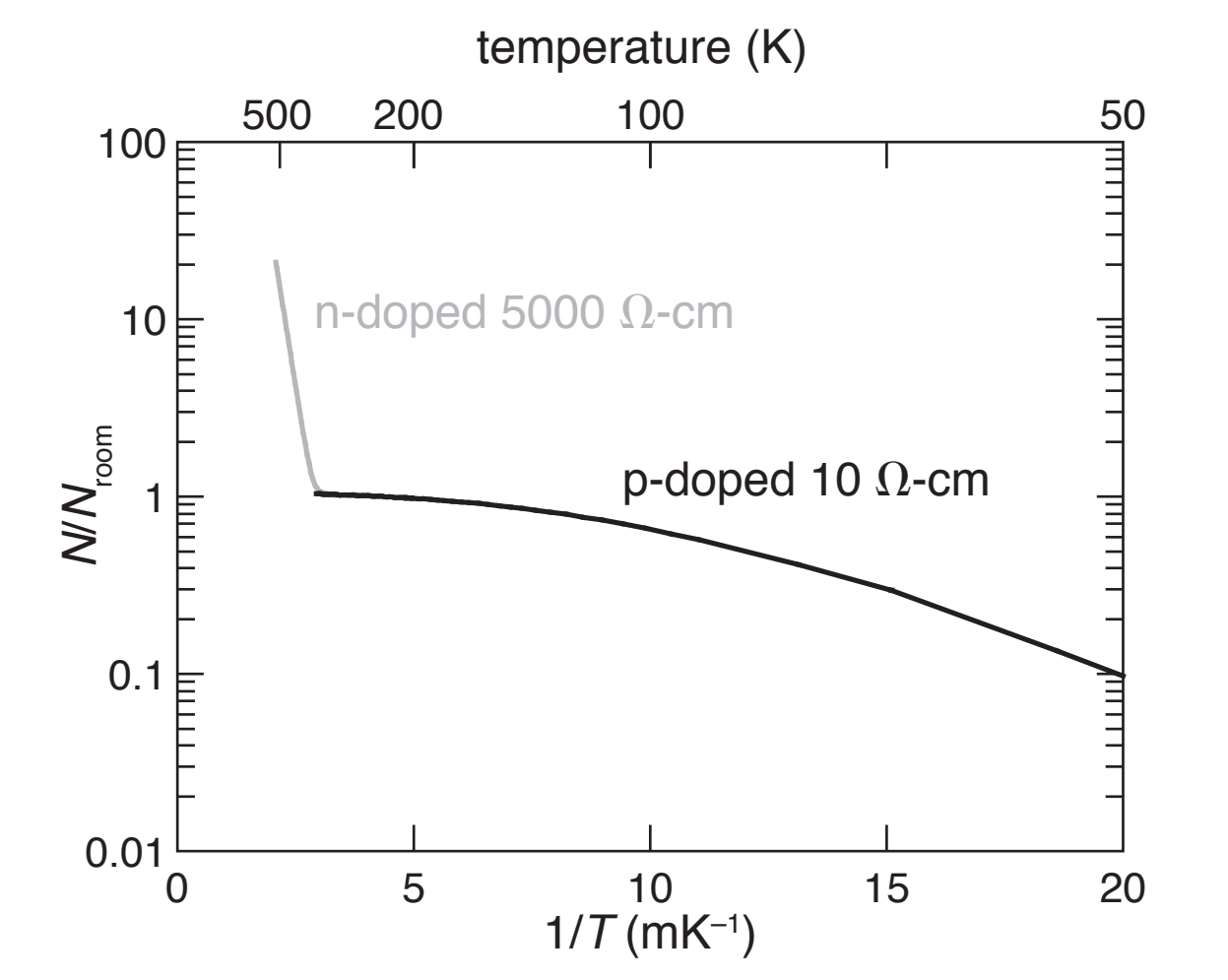
Hall measurements



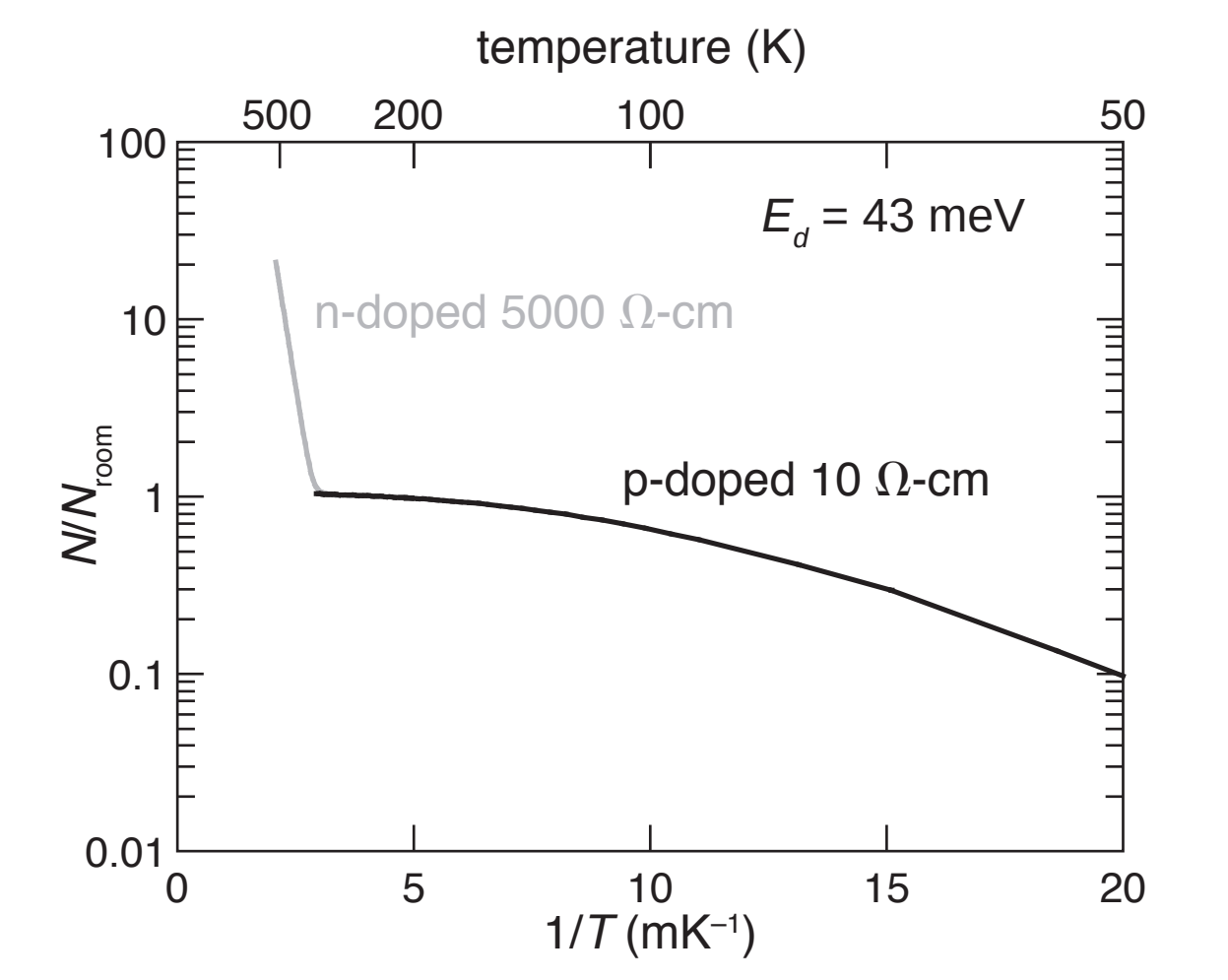
Hall measurements



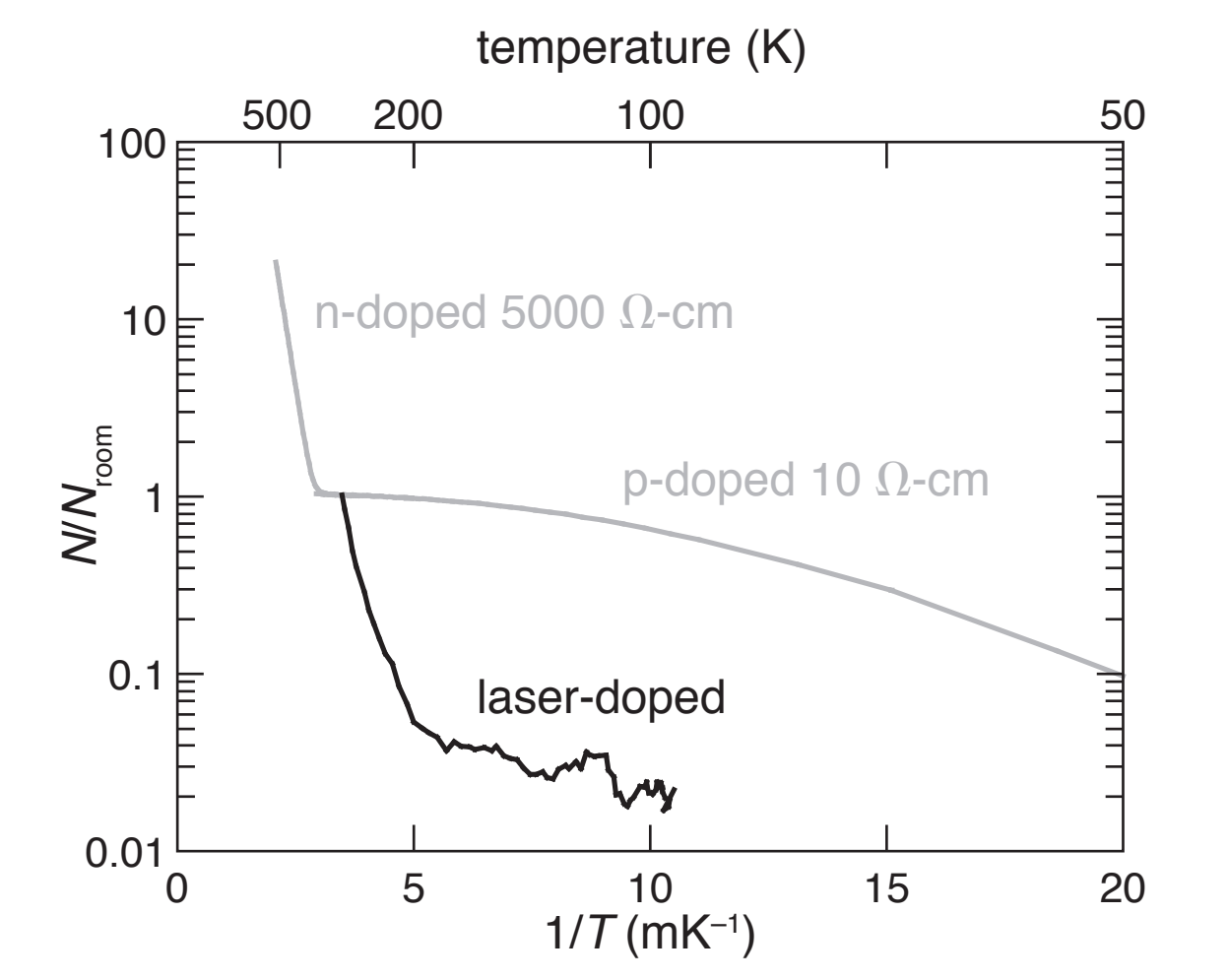
Hall measurements



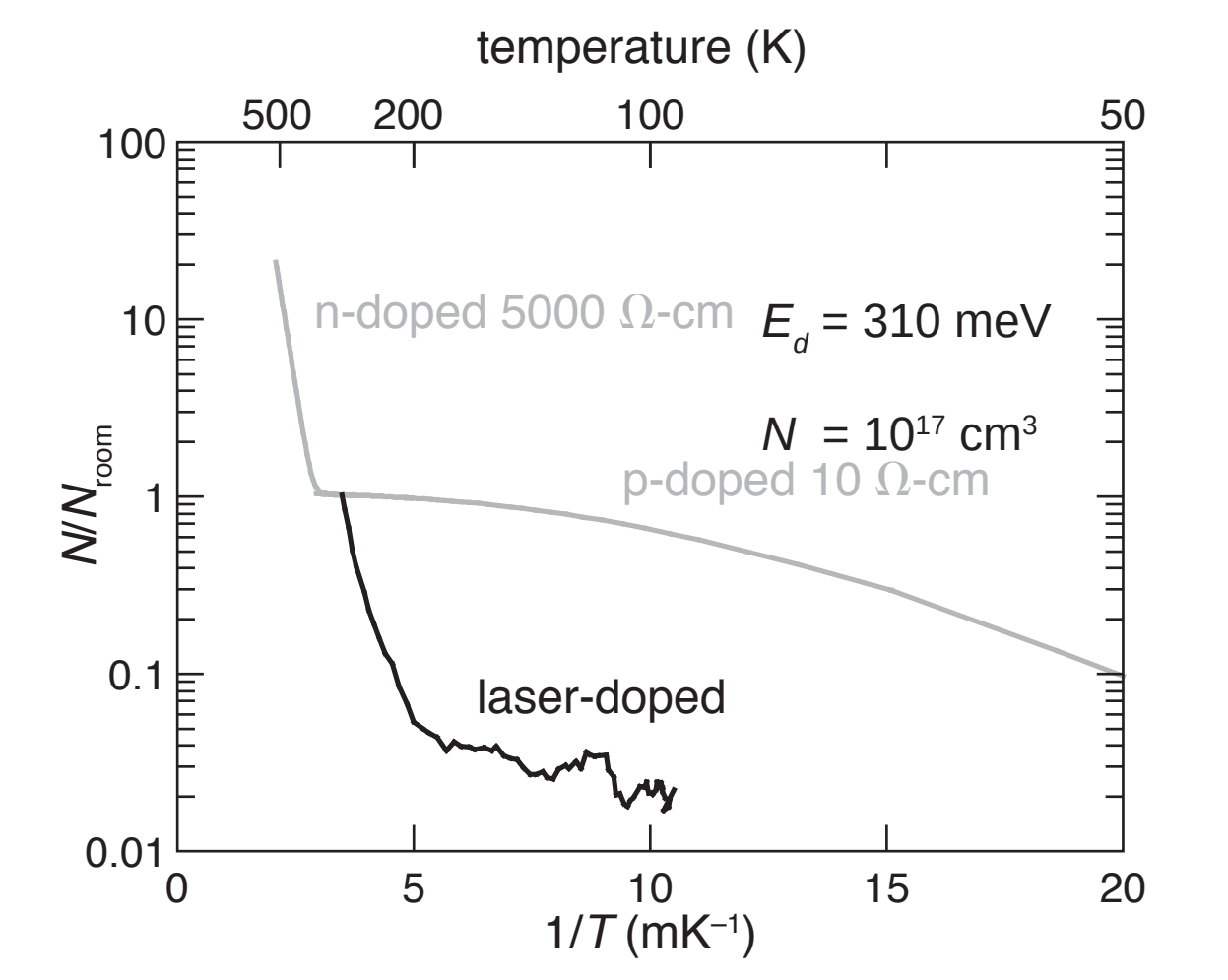
Hall measurements



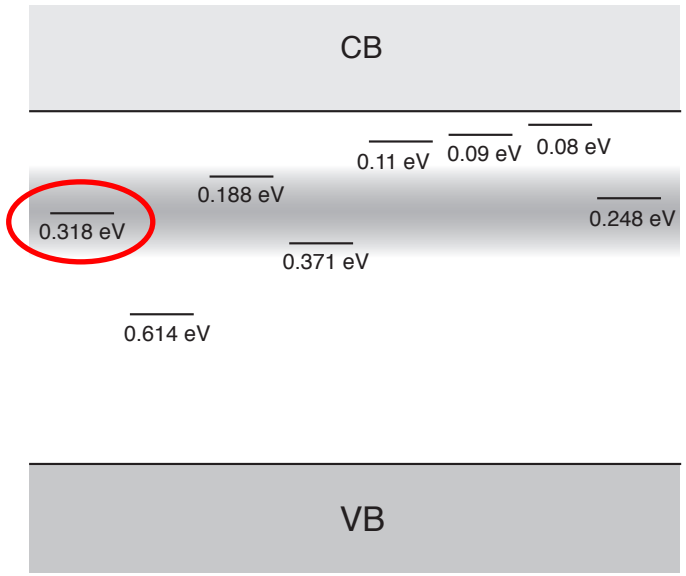
Hall measurements



Hall measurements



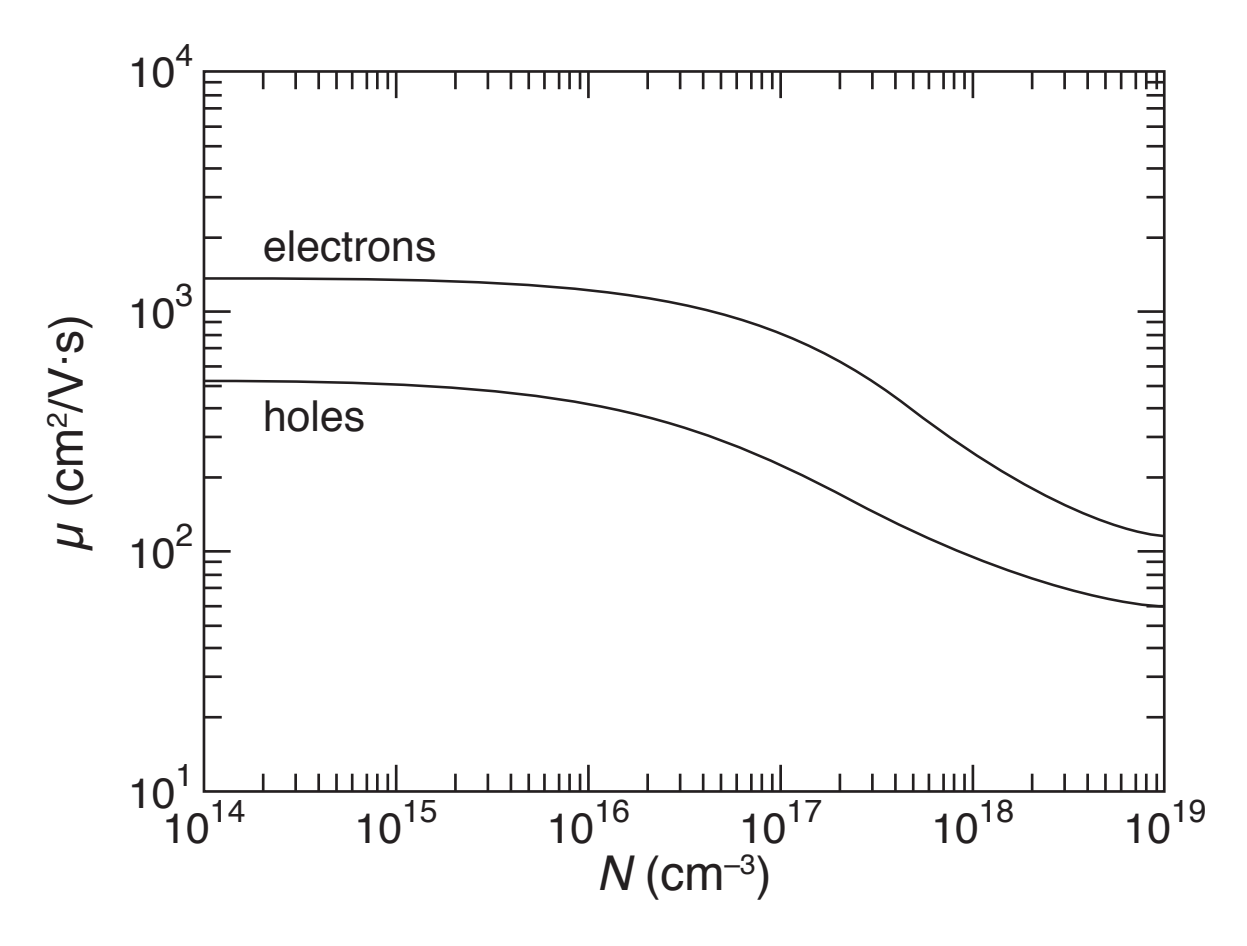
impurity (donor) band centered at 310 meV



1 structure

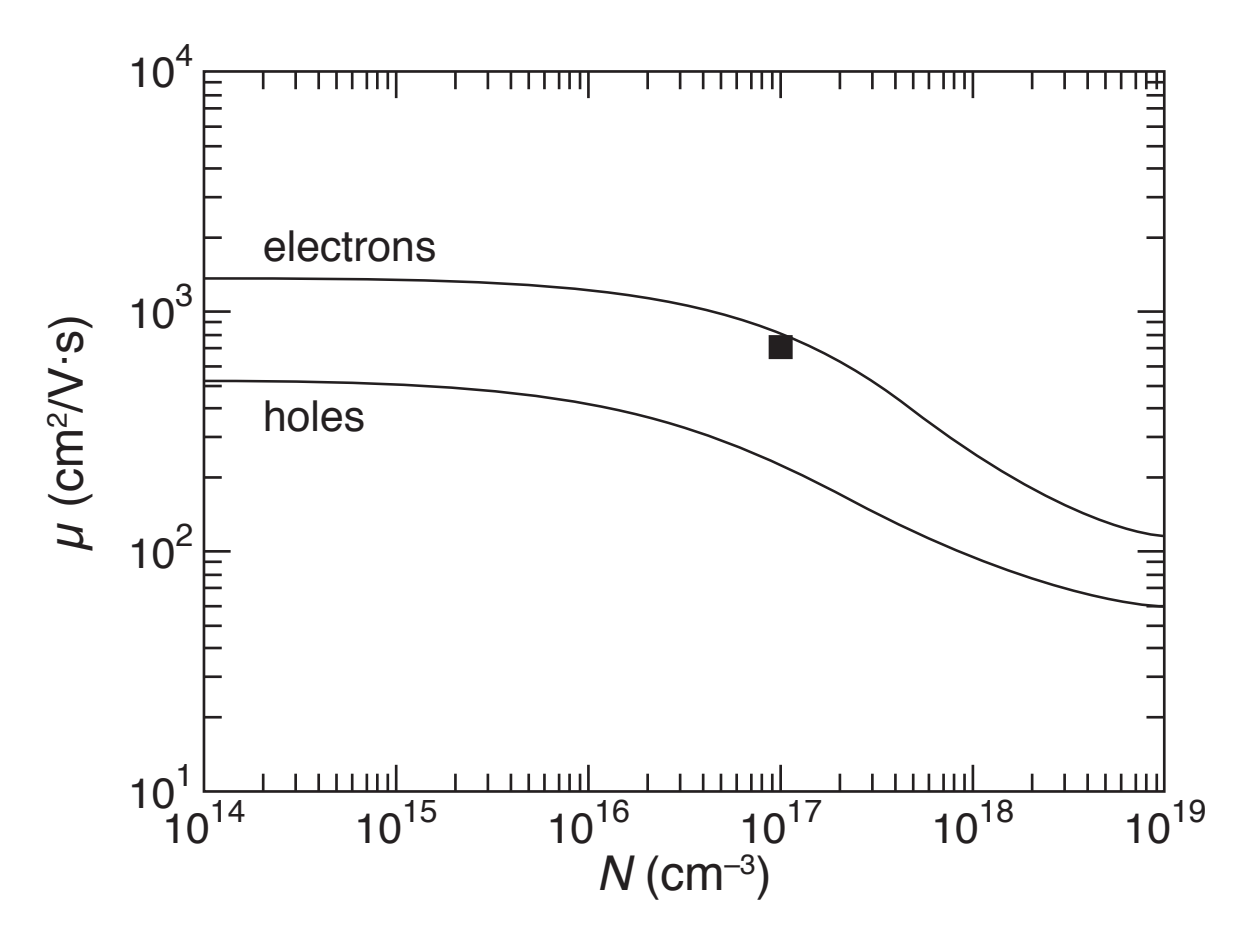
2 OE properties

majority carrier mobility



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

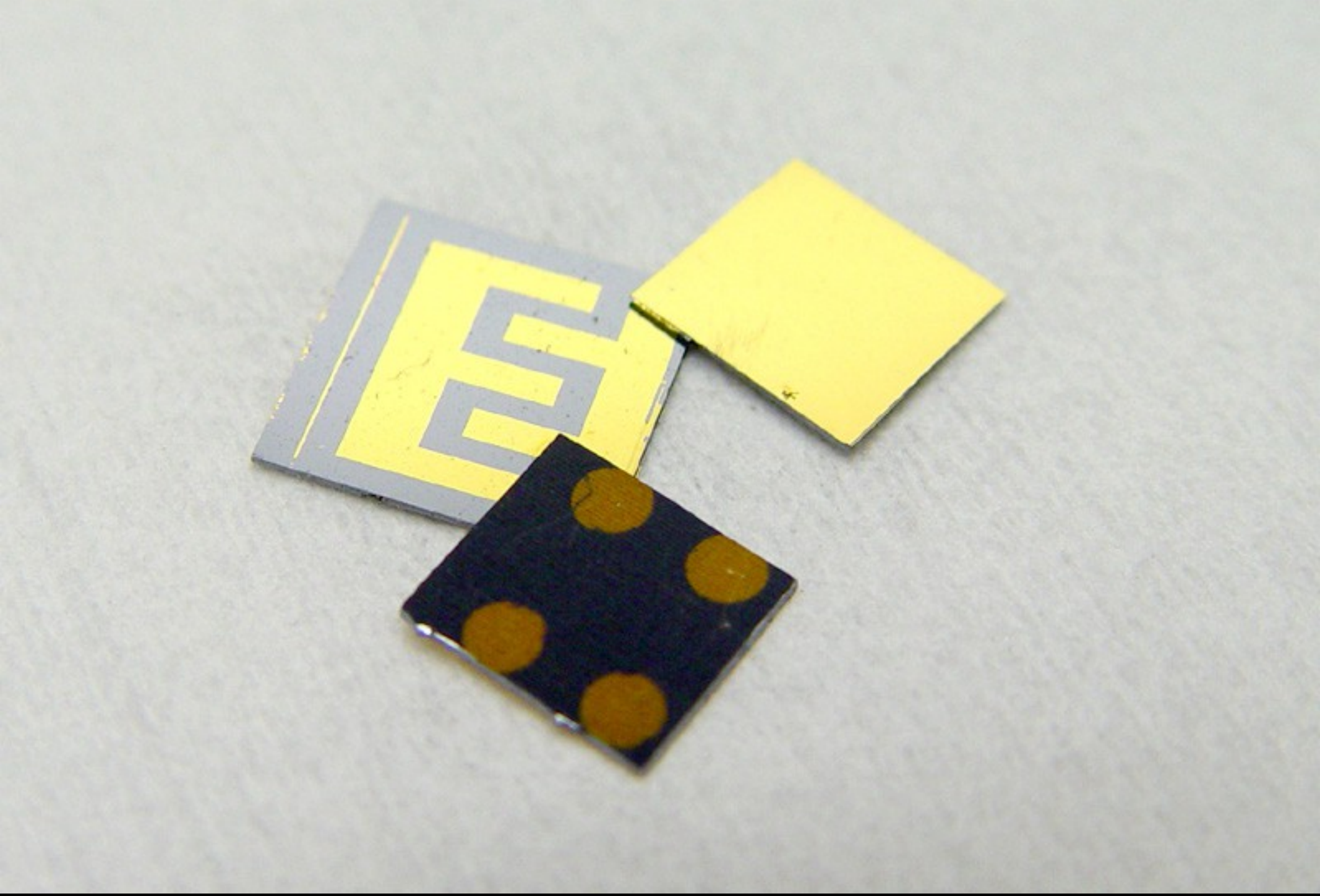
majority carrier mobility



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

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



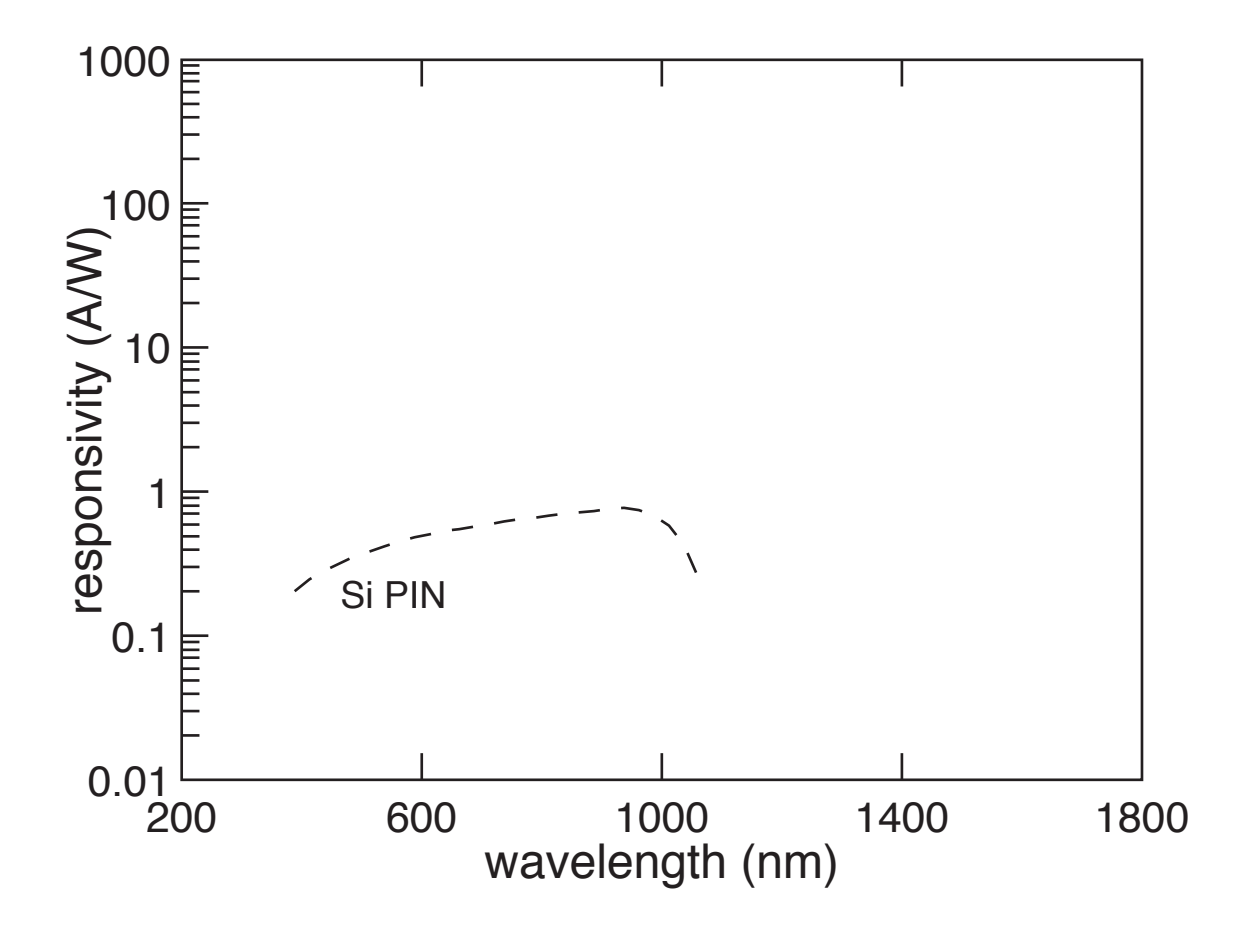
1 structure 2 OE properties 3 devices

1 structure

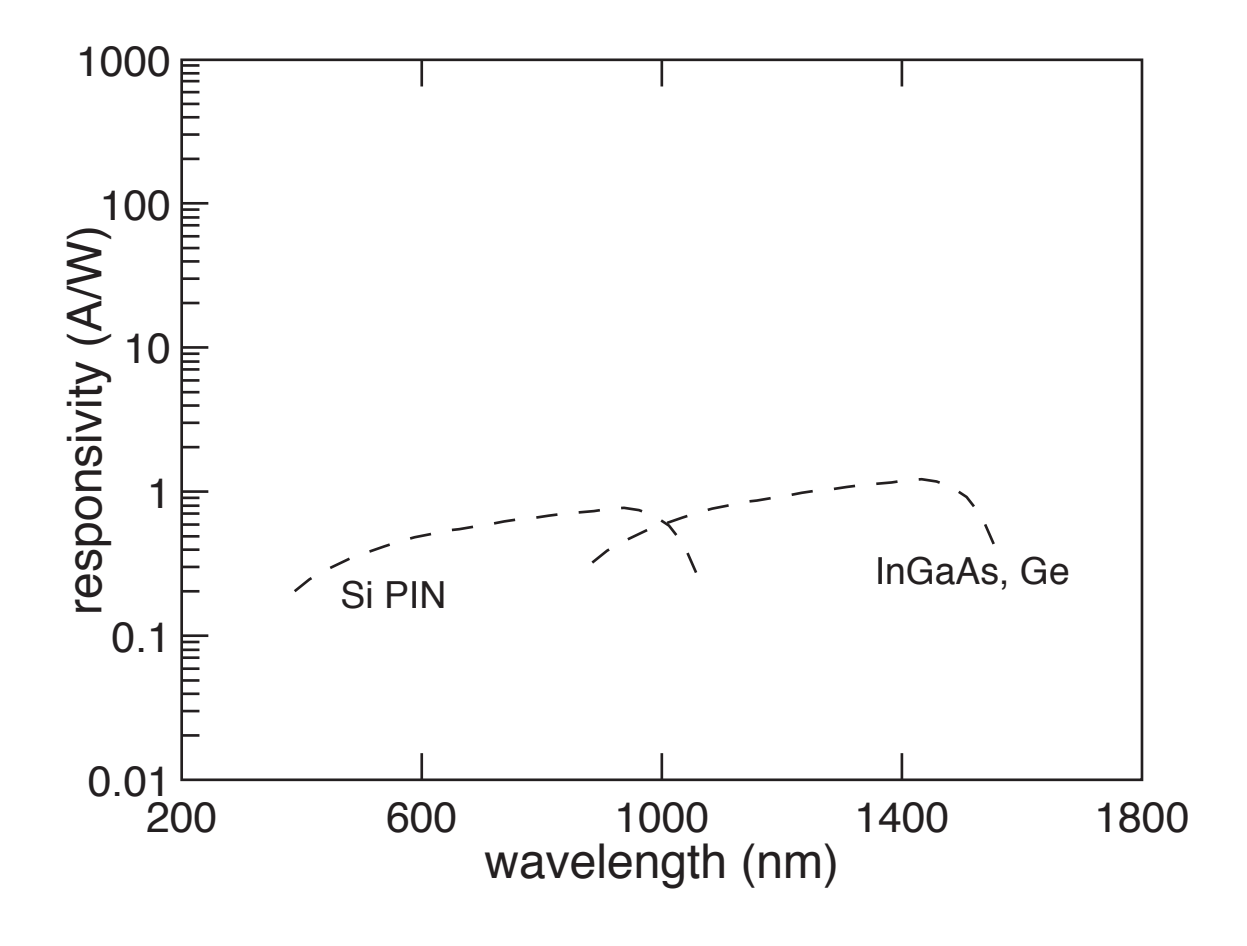
2 OE properties

3 devices

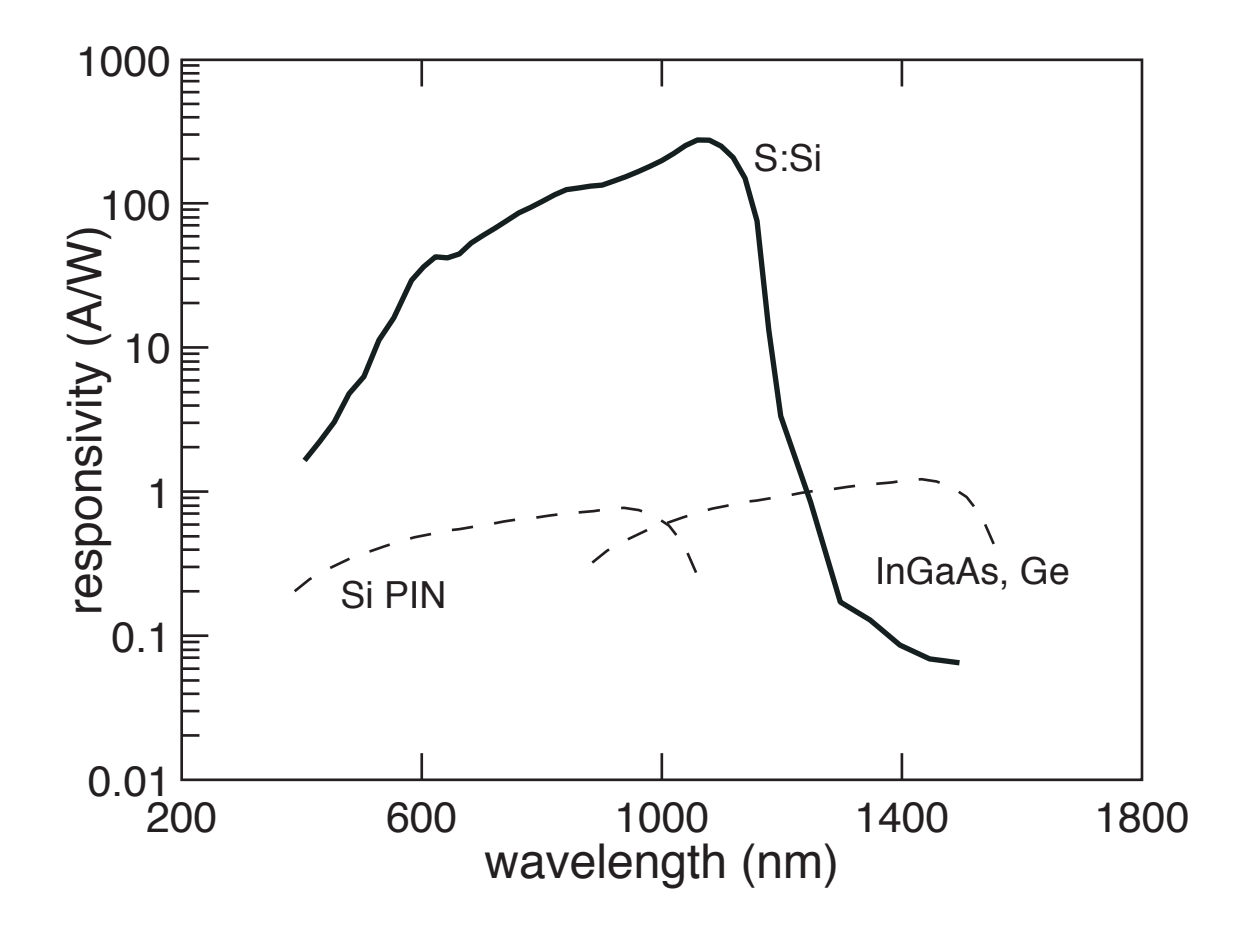
responsivity



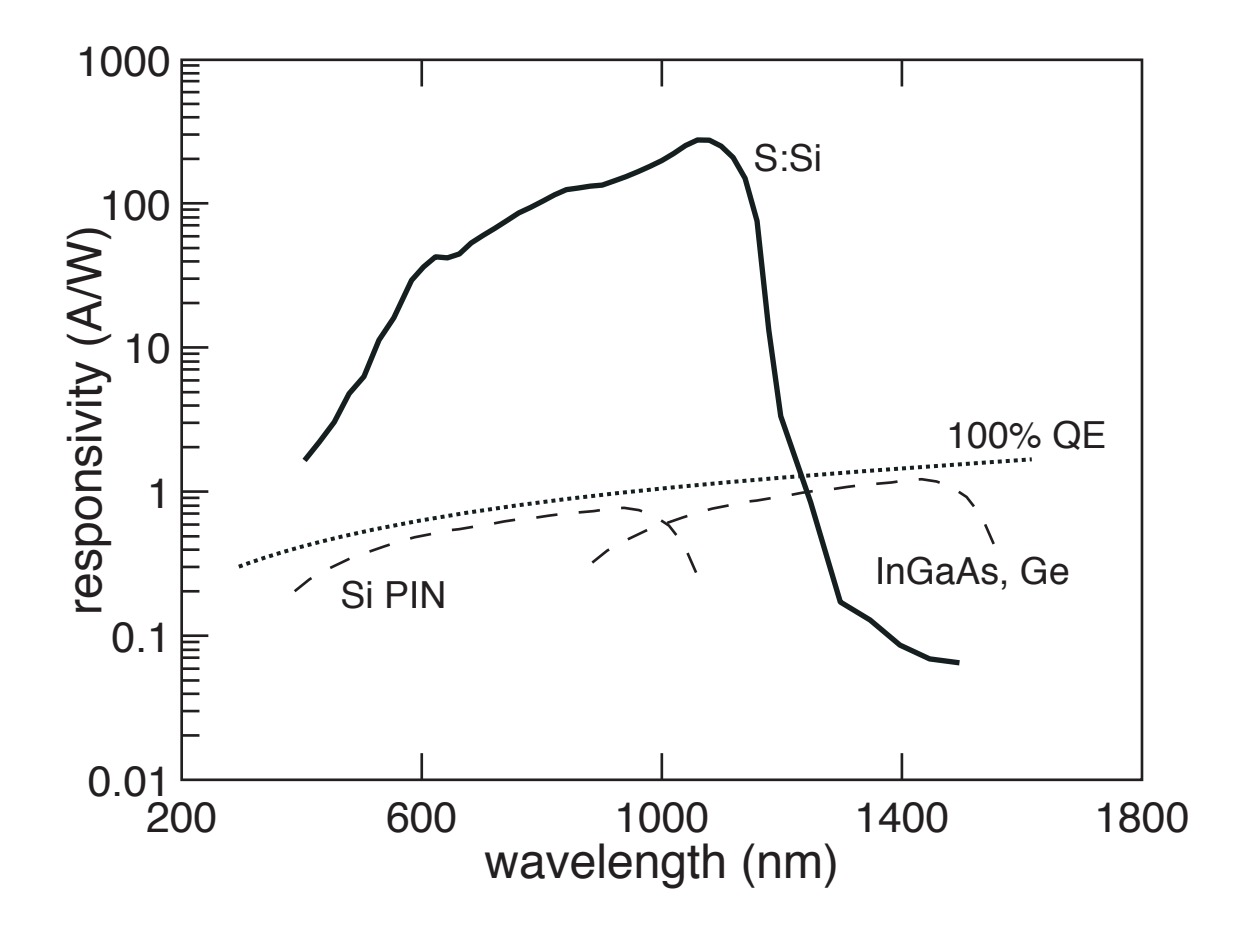
responsivity



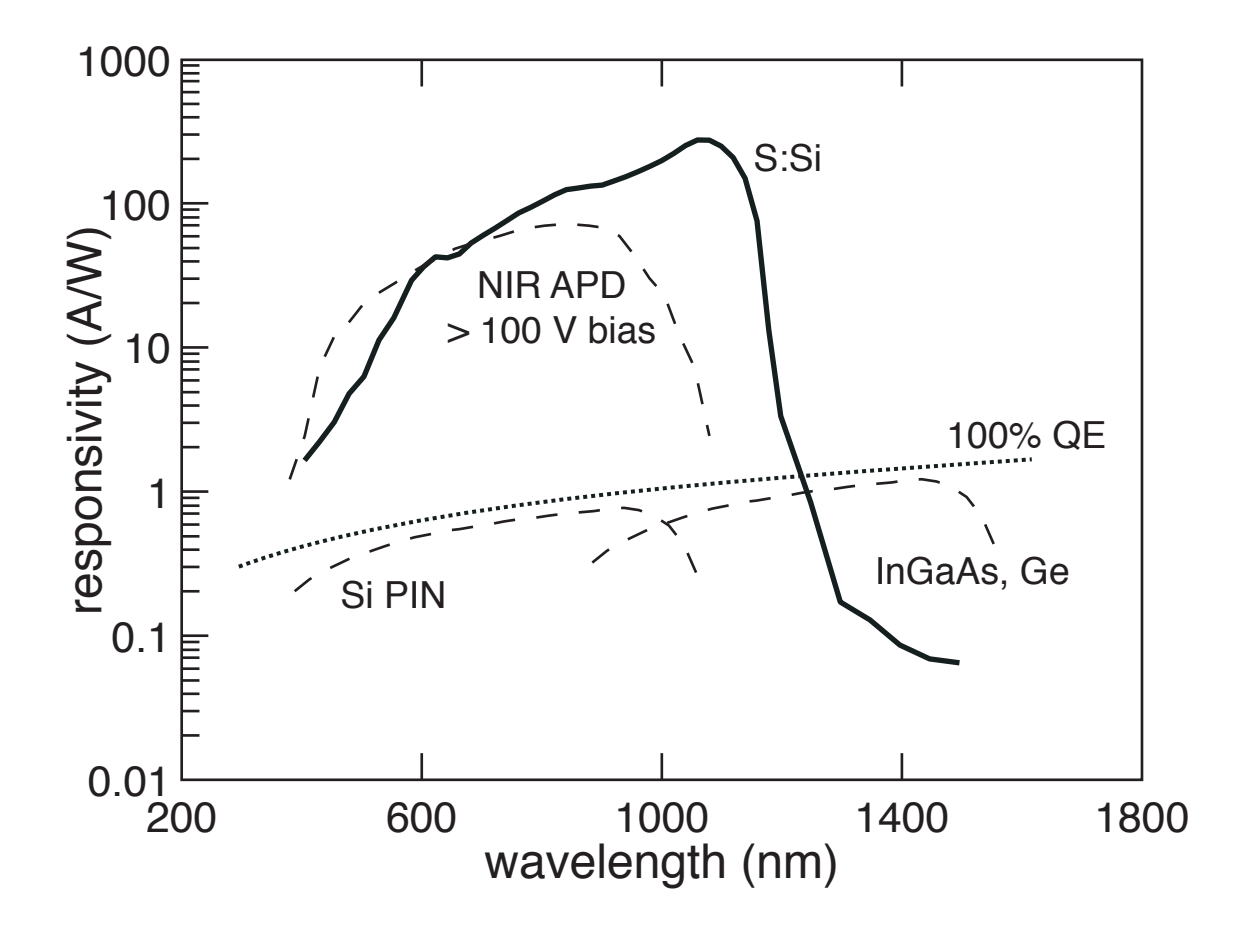
responsivity



responsivity

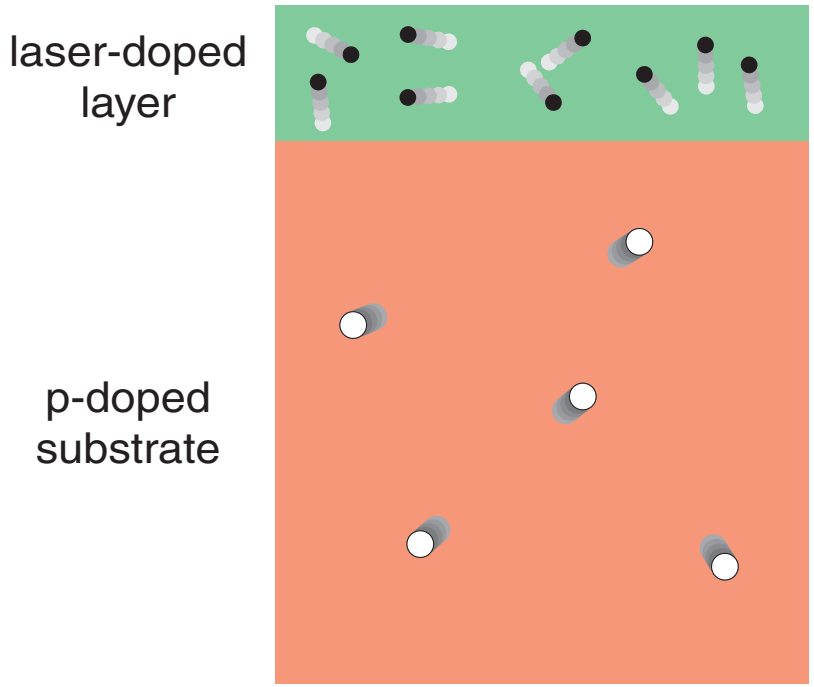


responsivity

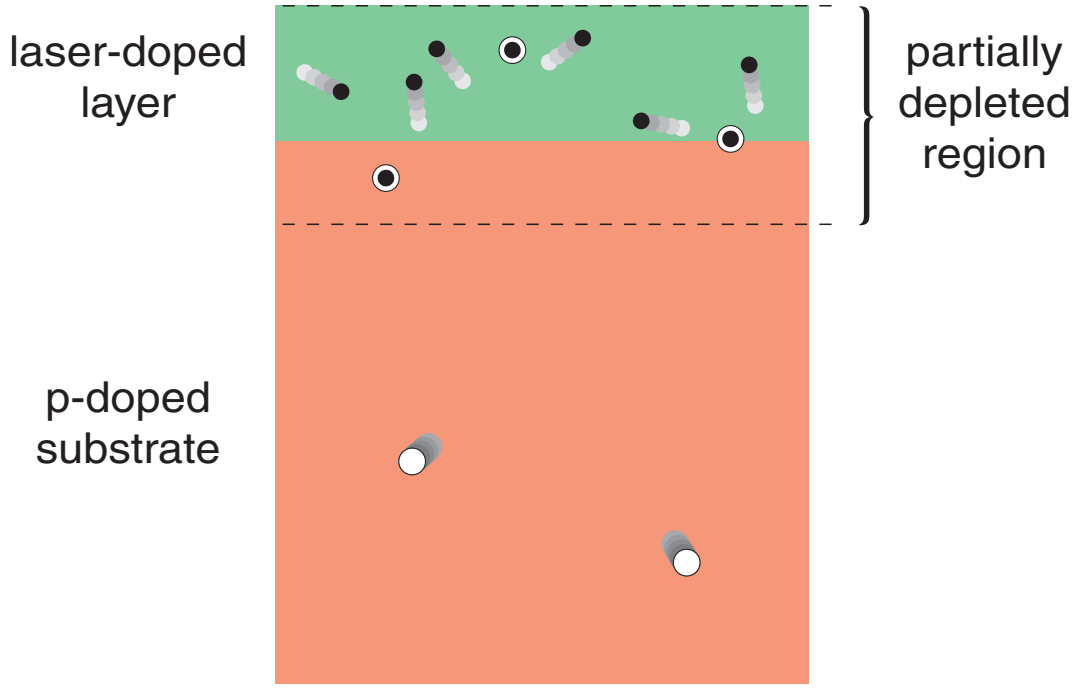


What causes gain?

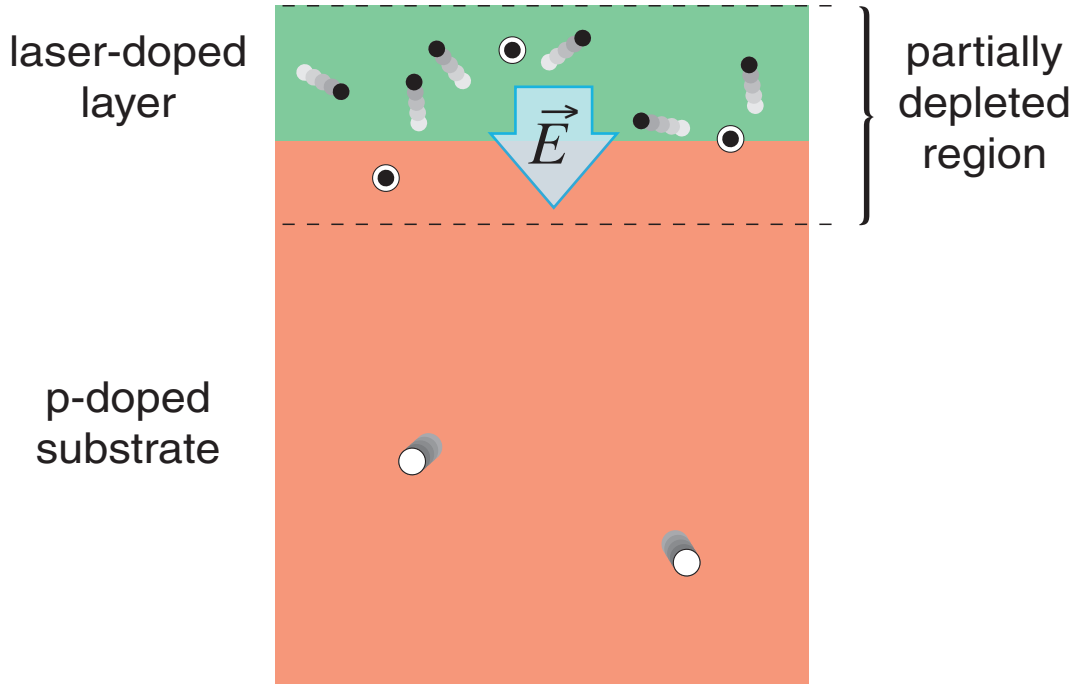
- impact excitation (avalanching)
- carrier lifetime >> transit time (photoconductive gain)
- some other mechanism



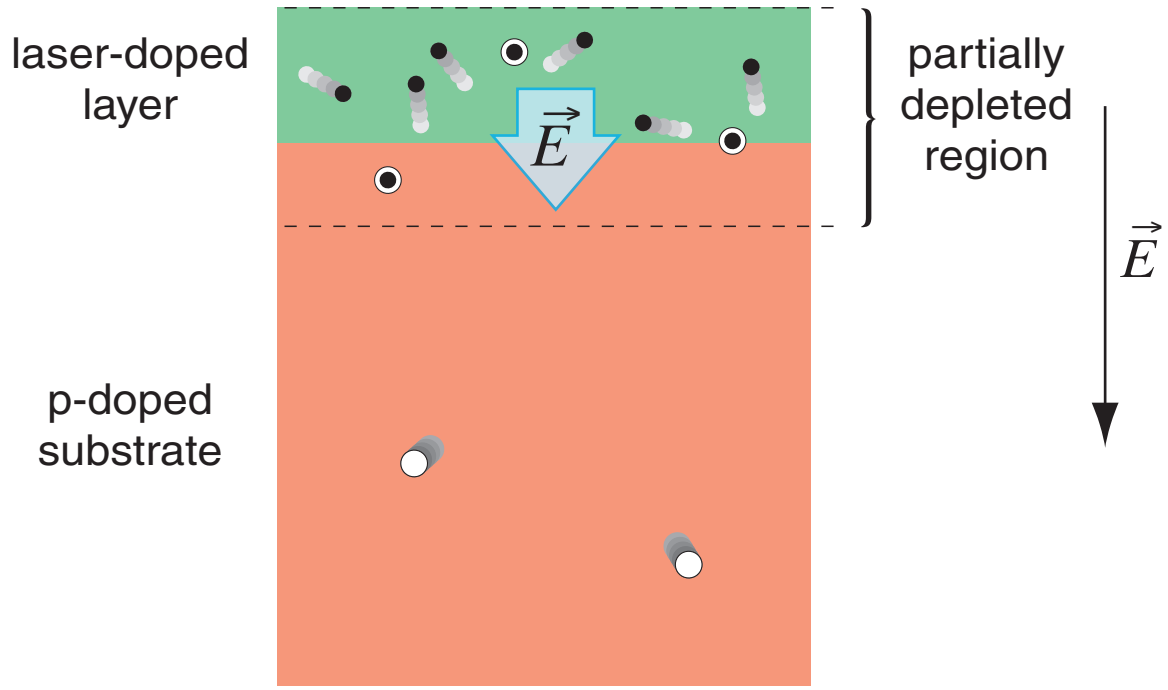
“pl junction”



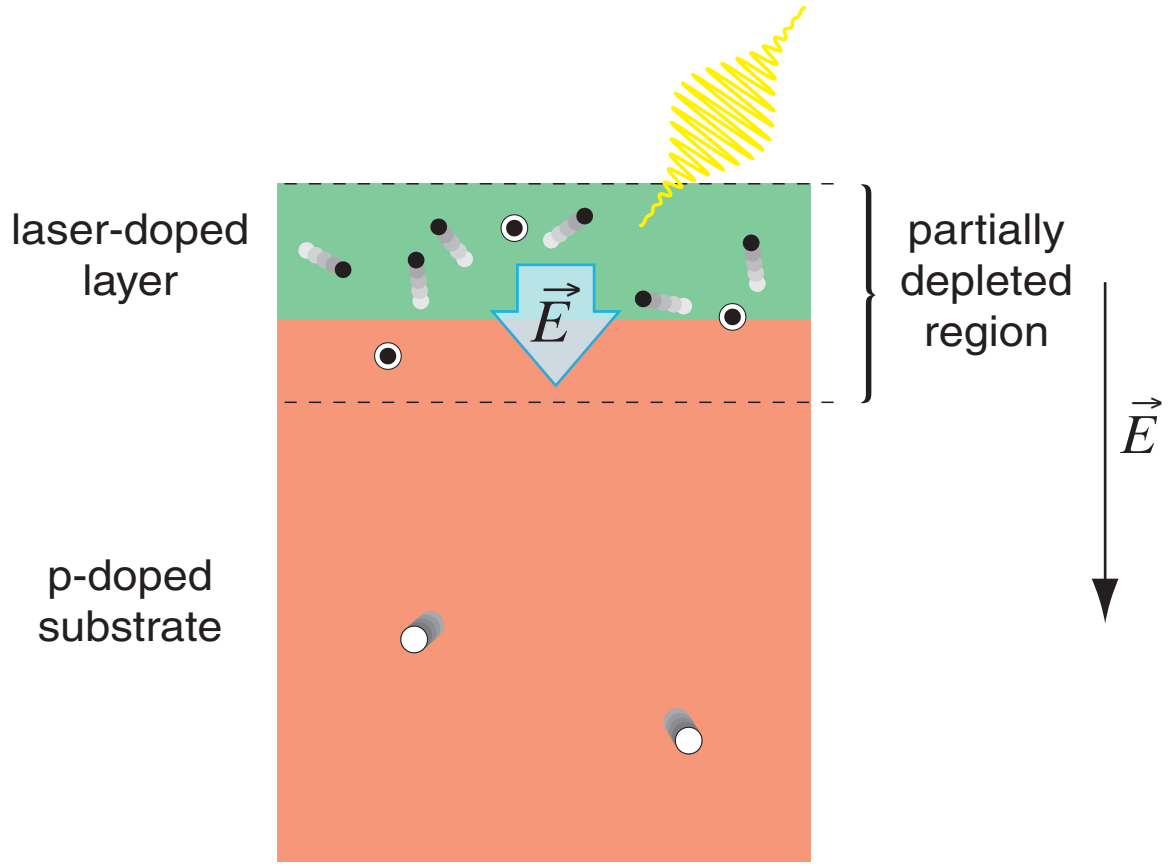
formation of partially depleted region



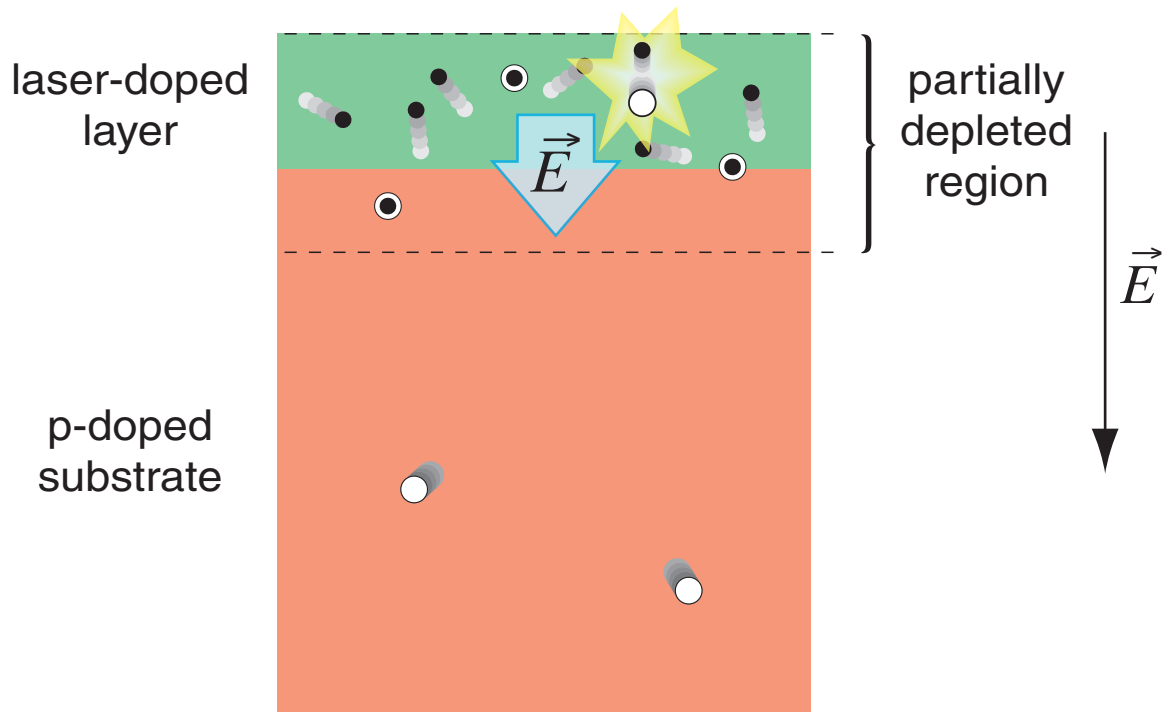
formation of partially depleted region



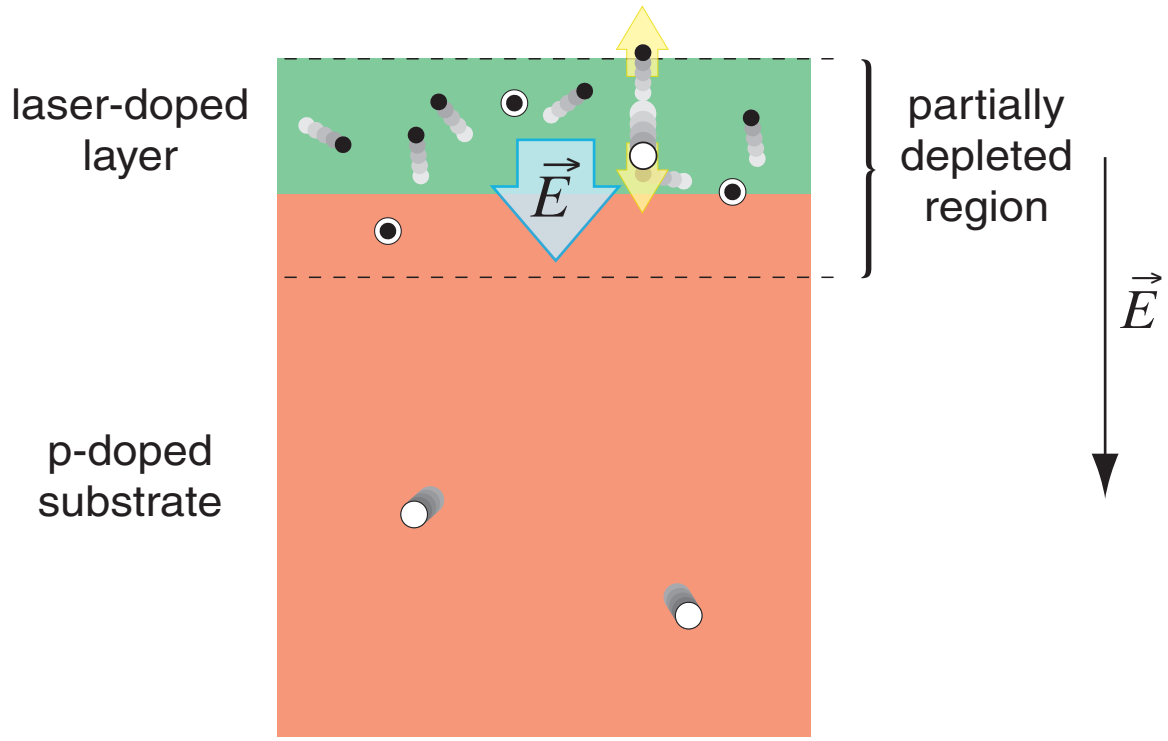
apply backward bias…



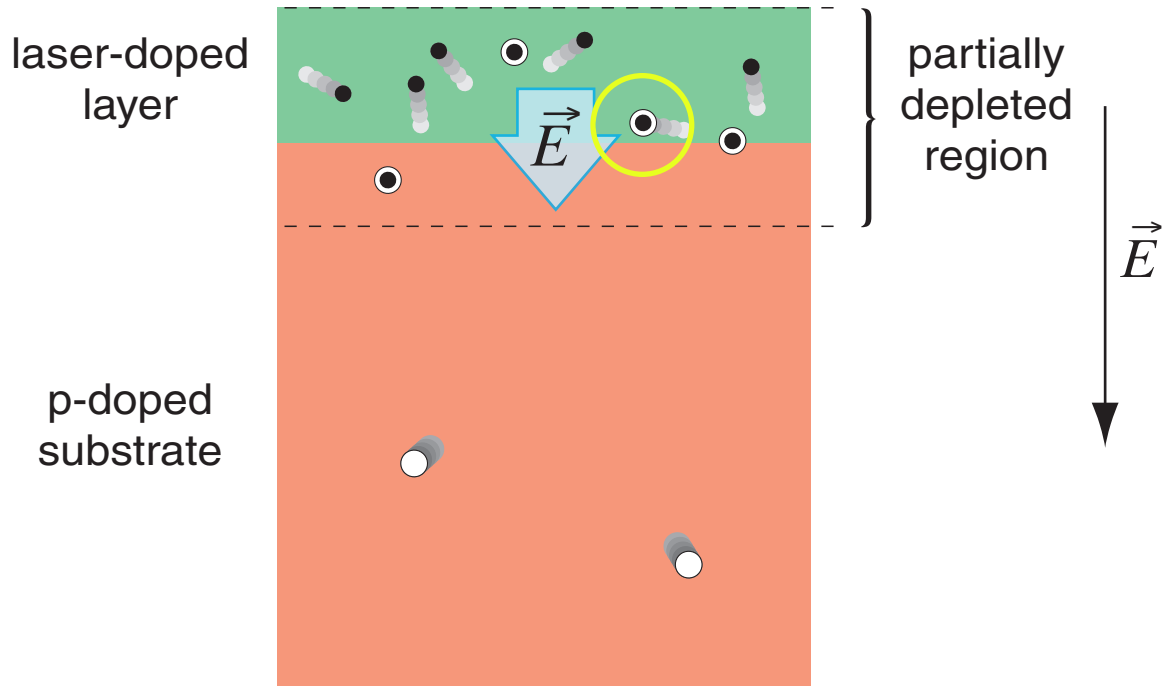
…incident photon generates electron-hole pair…



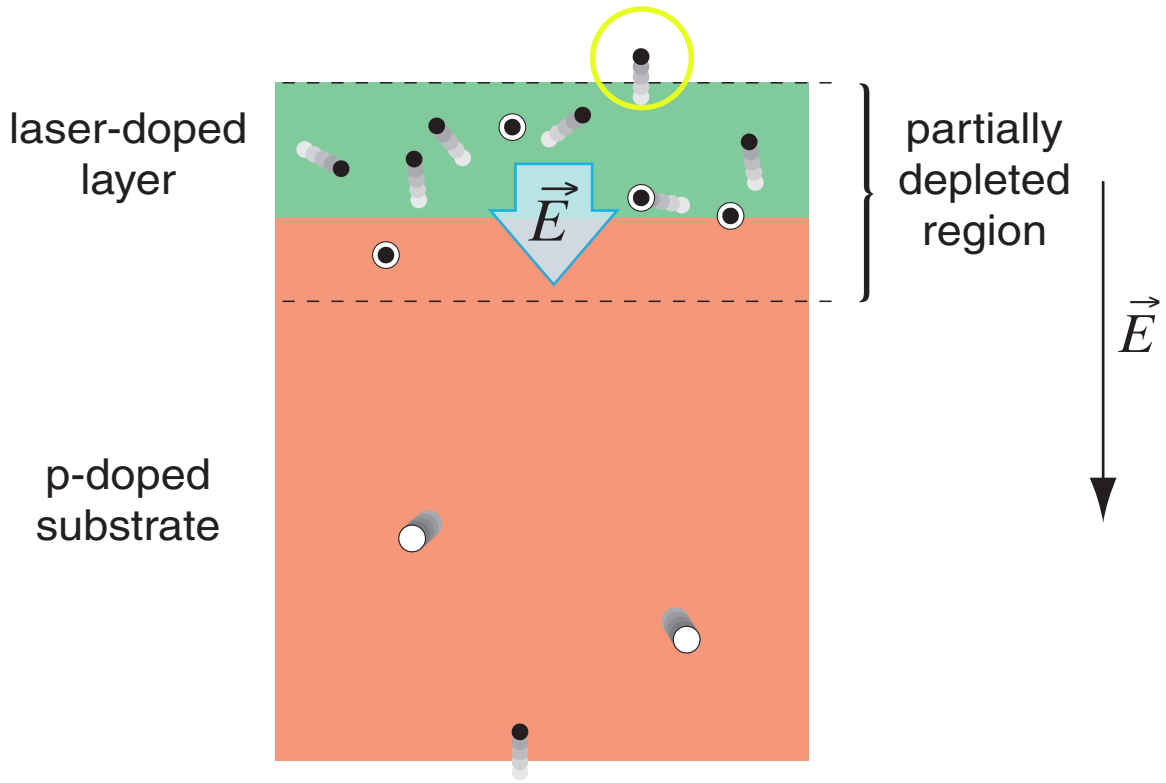
…incident photon generates electron-hole pair…



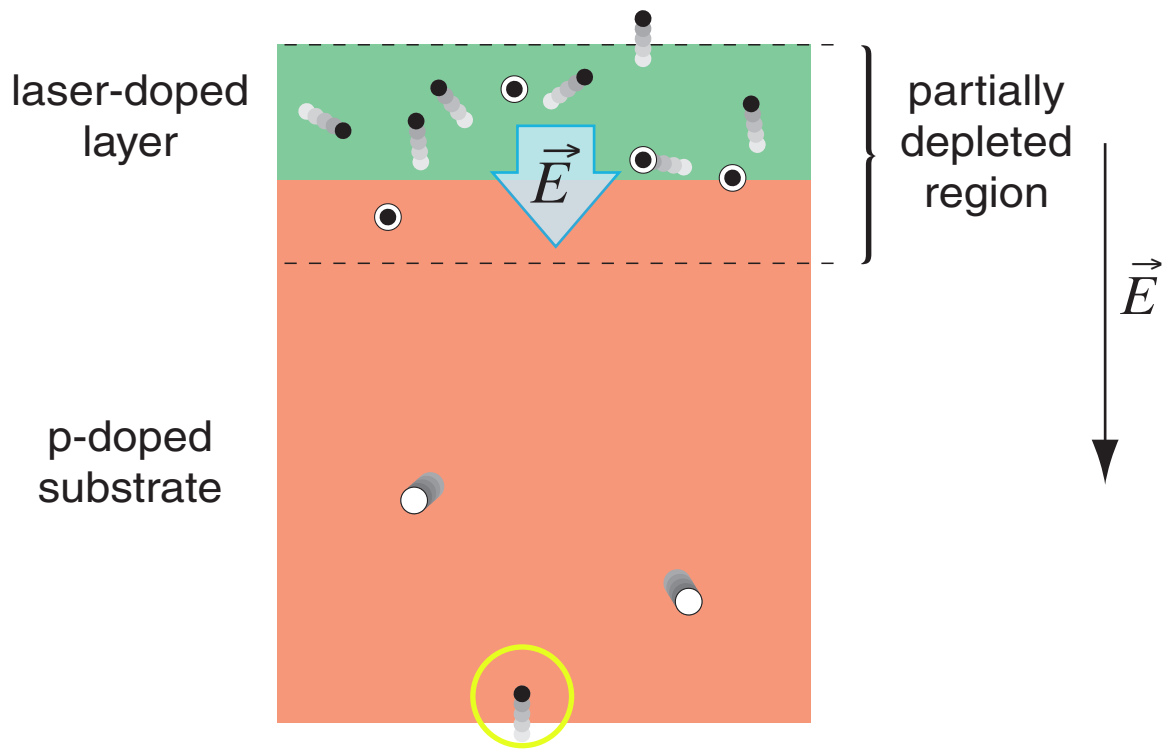
…carriers accelerate away from each other…



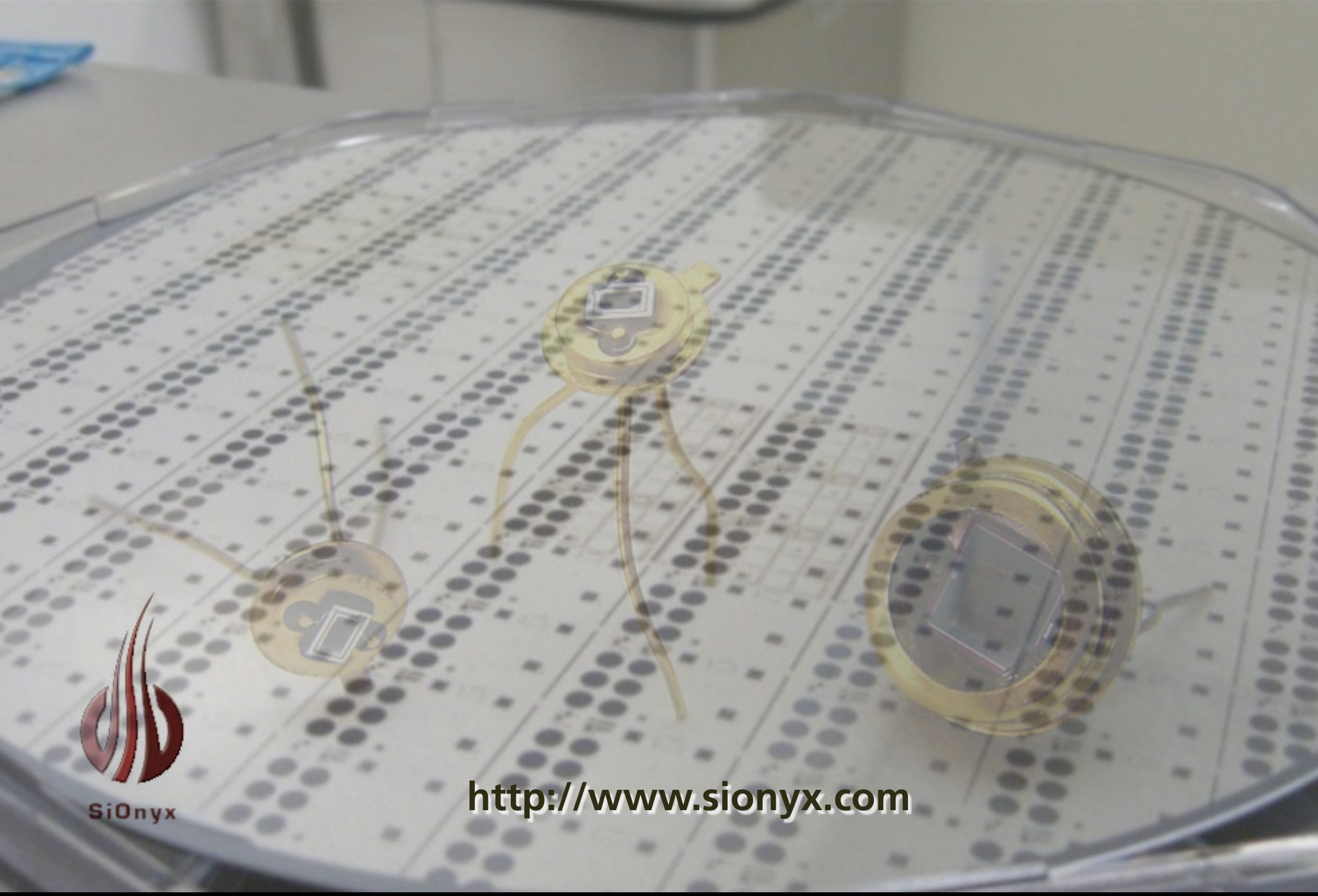
...hole is trapped



meanwhile electron exits sample…



…and source provides new electron



1 structure

2 OE properties

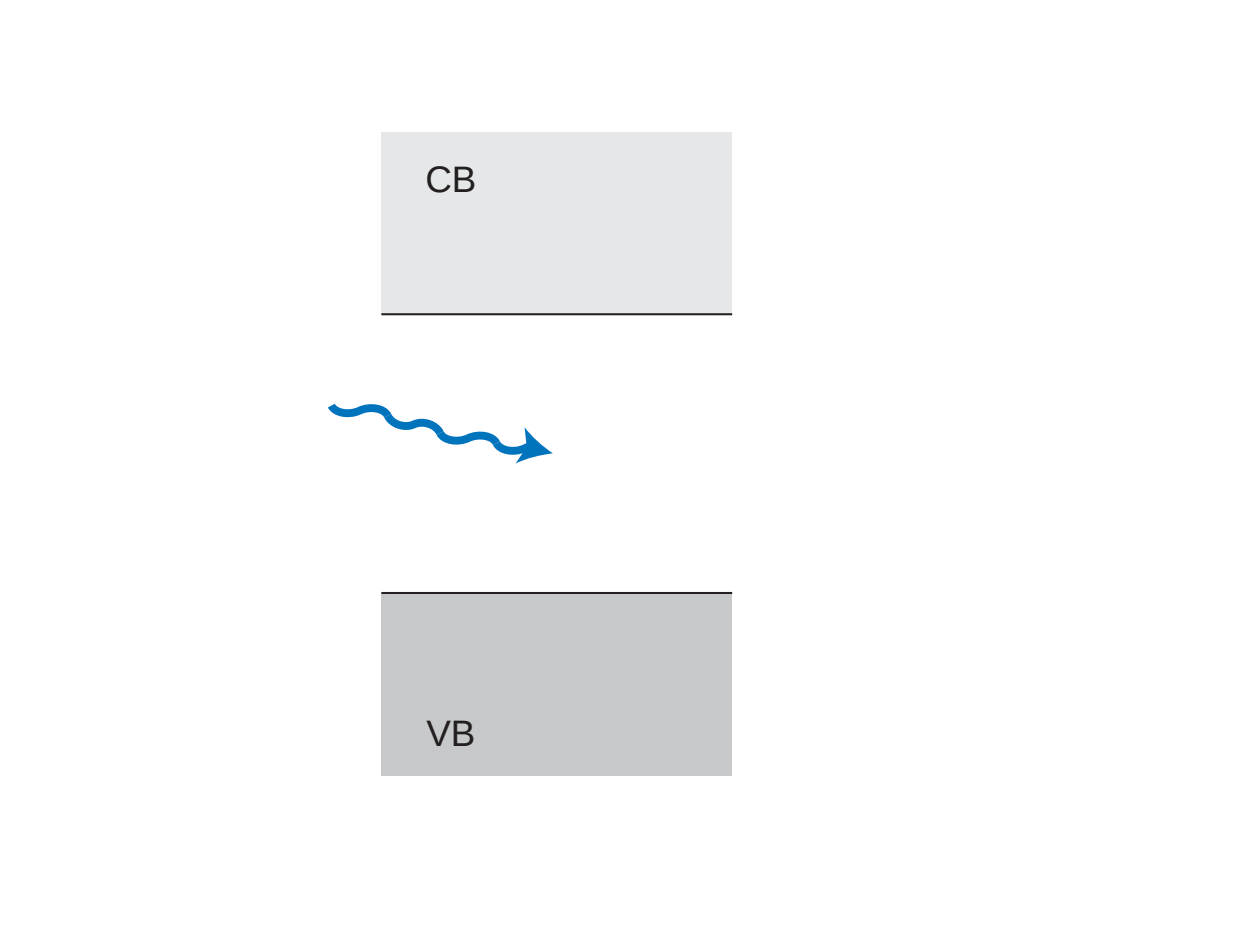
3 devices

Potential benefits for photovoltaics

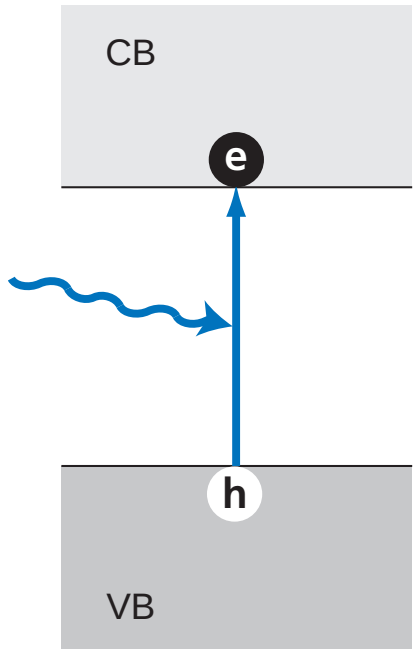
- surface structure
- absorption in submicrometer layer
- extended IR absorption
- intermediate band

1 structure 2 OE properties 3 devices

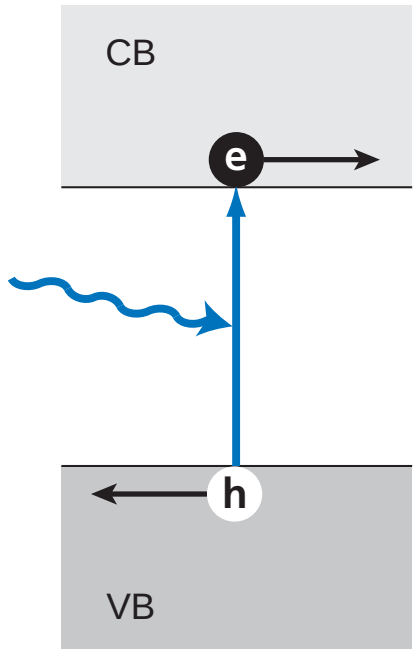
photon with gap energy



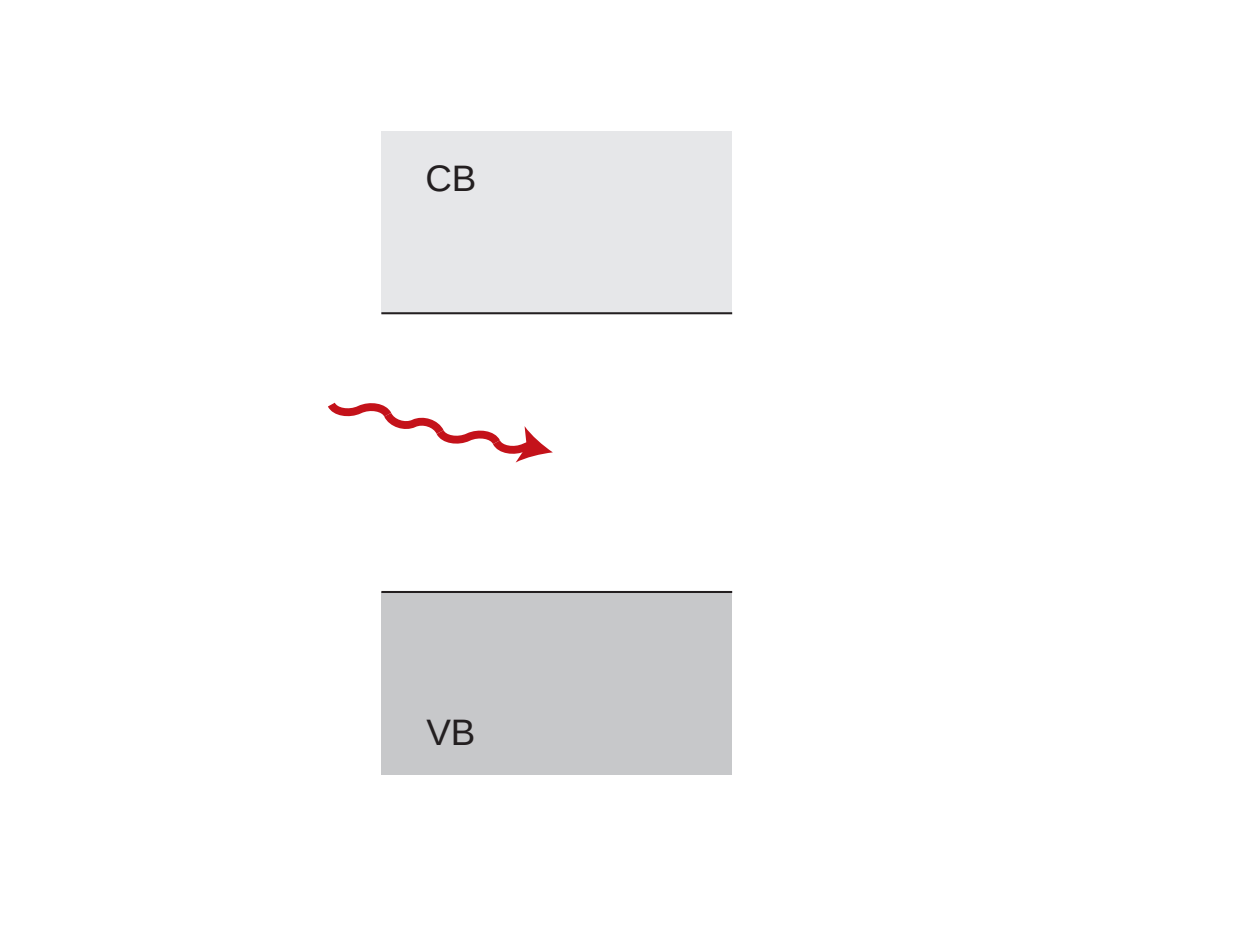
photon creates electron-hole pair…



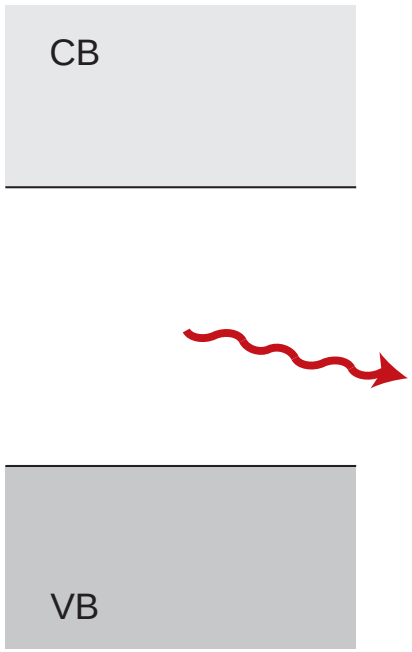
…whose energy can be extracted



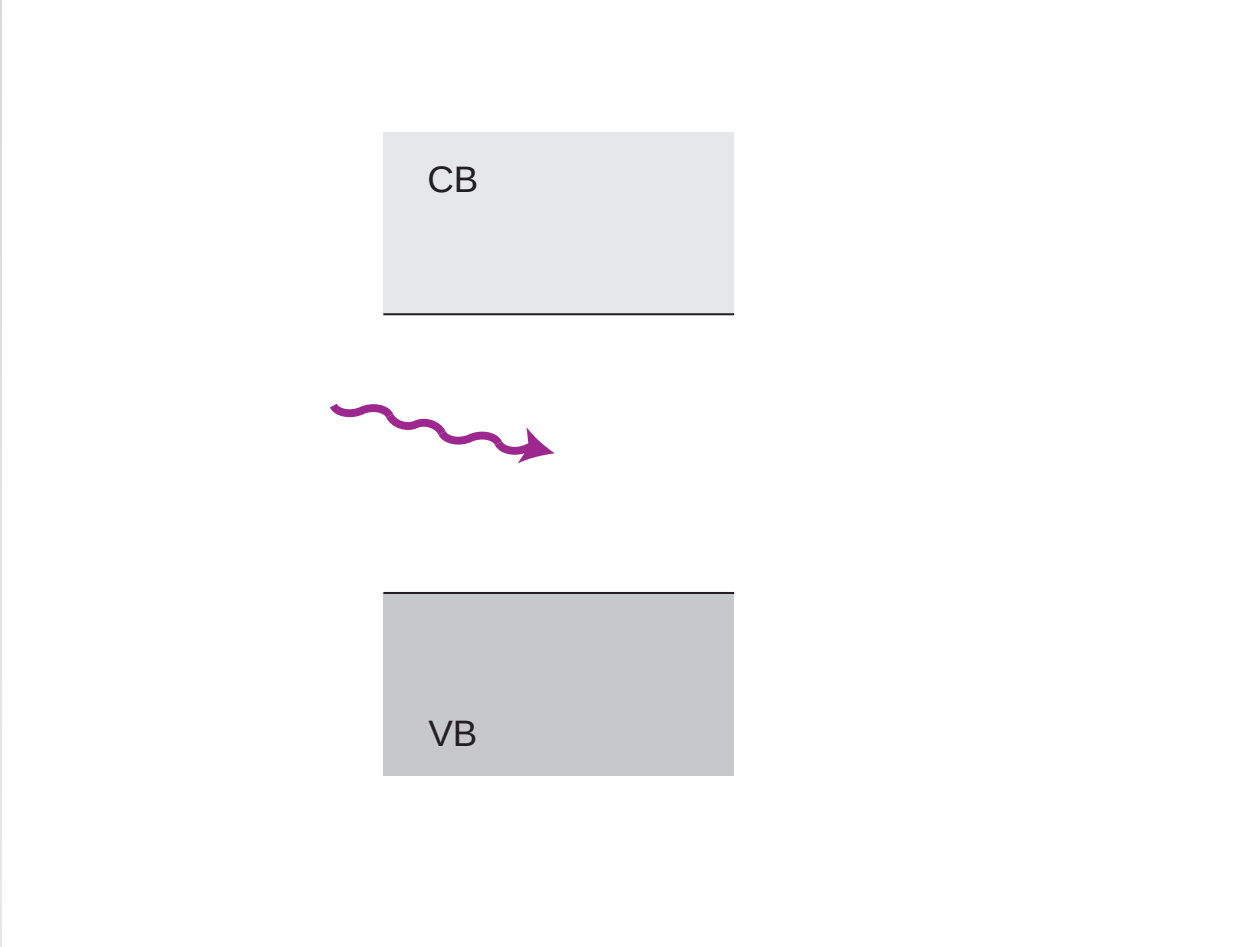
photons with energy smaller than gap…



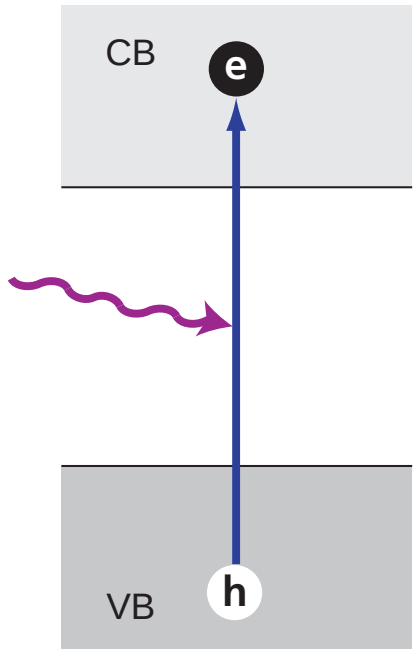
…do not get absorbed



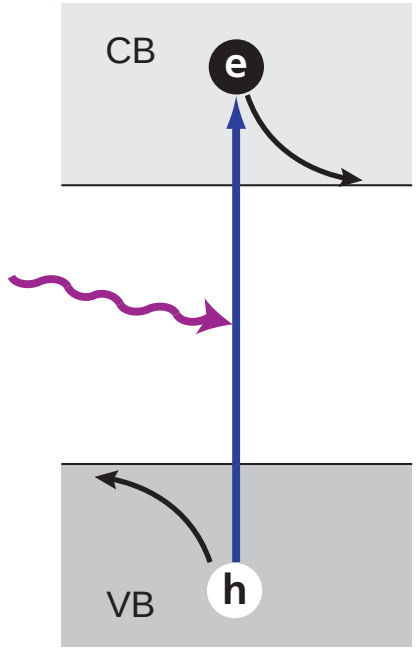
photons with energy larger than the gap…



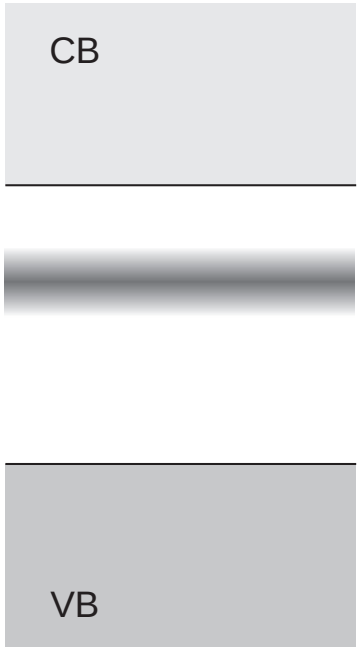
…create electron-hole pairs with excess energy…



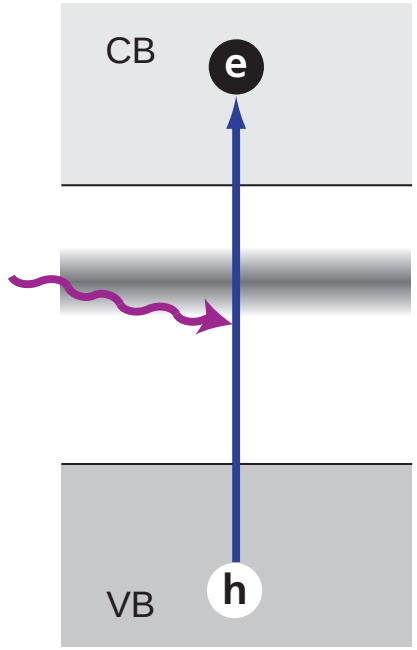
…which is lost rapidly



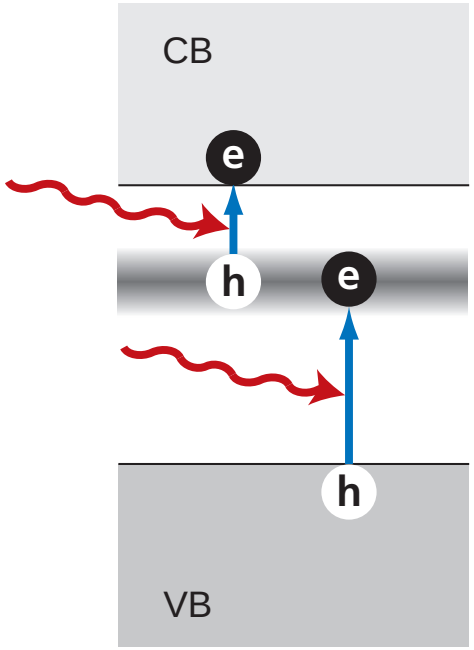
black silicon has an intermediate band



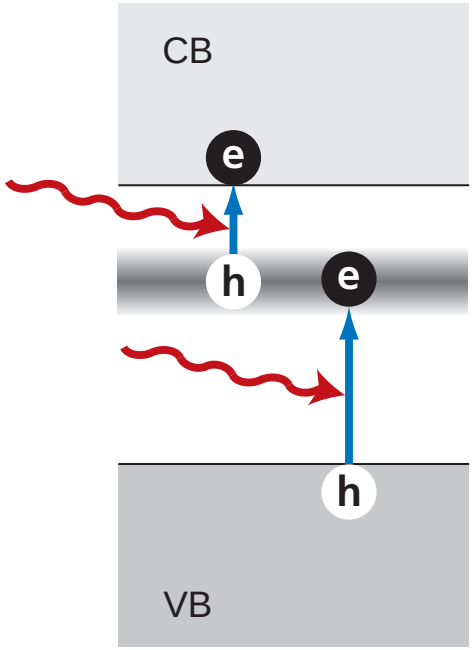
absorbs same photons as ordinary silicon…



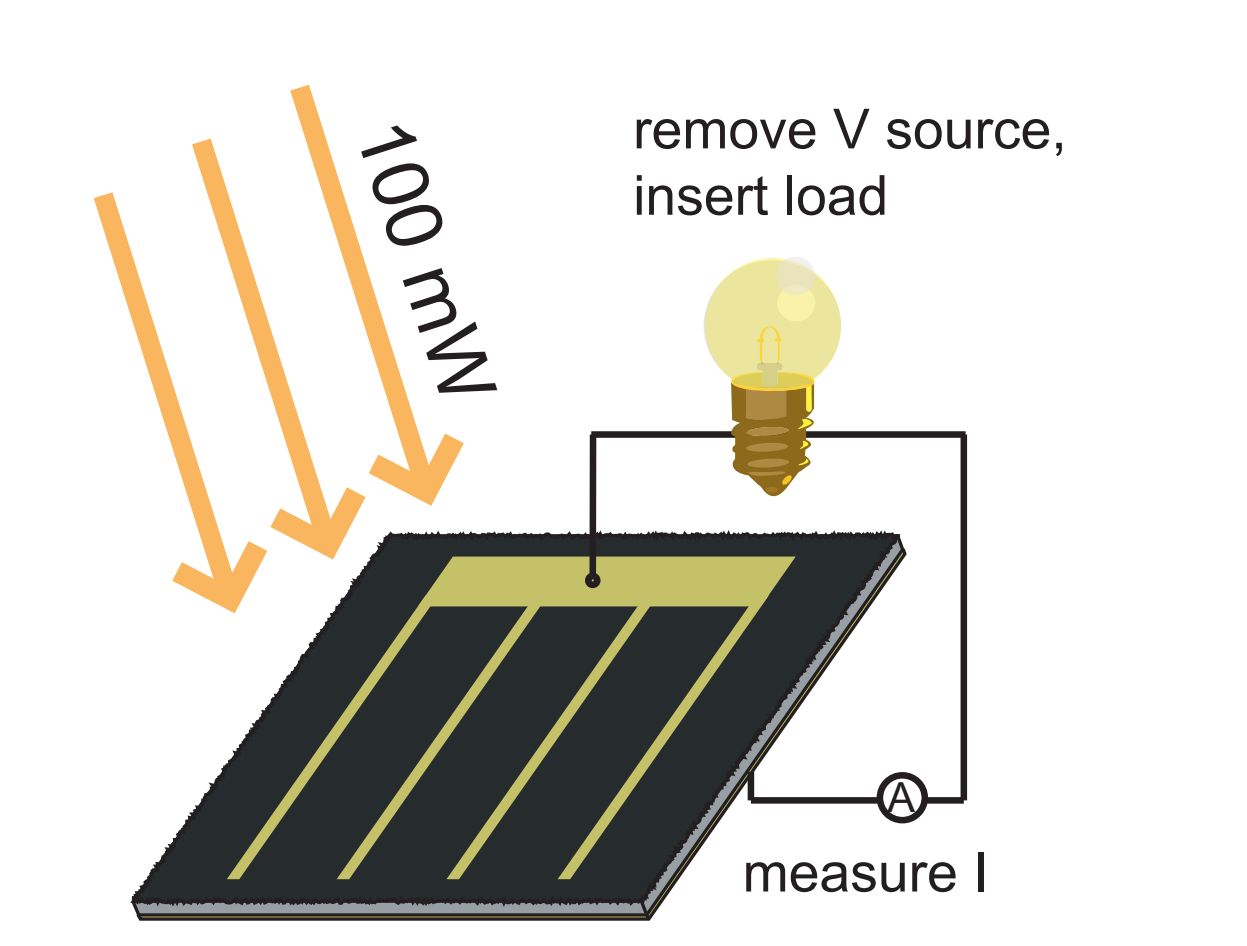
…but extends absorption to longer wavelengths



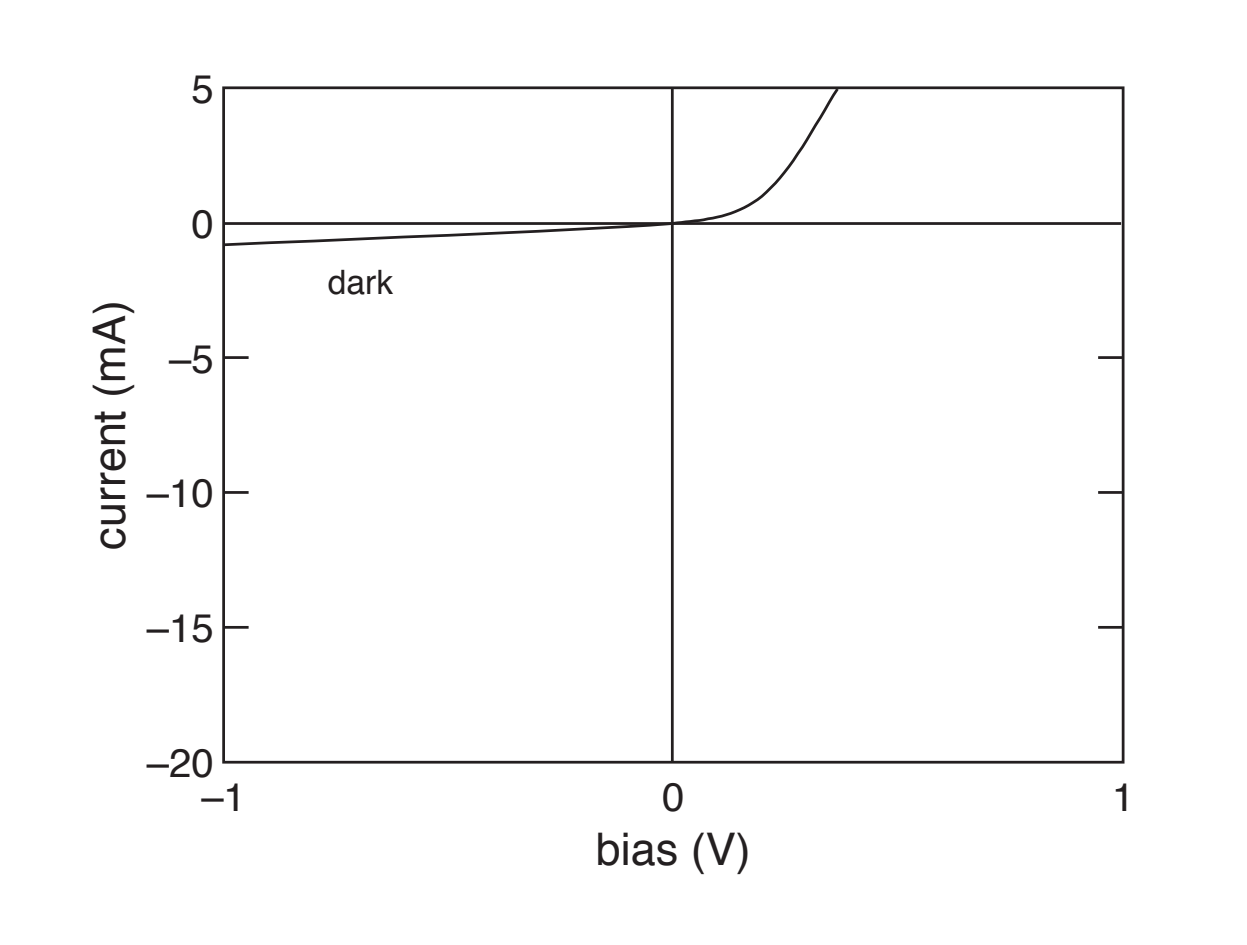
could theoretically get efficiencies over 50%



very preliminary photovoltaic cell

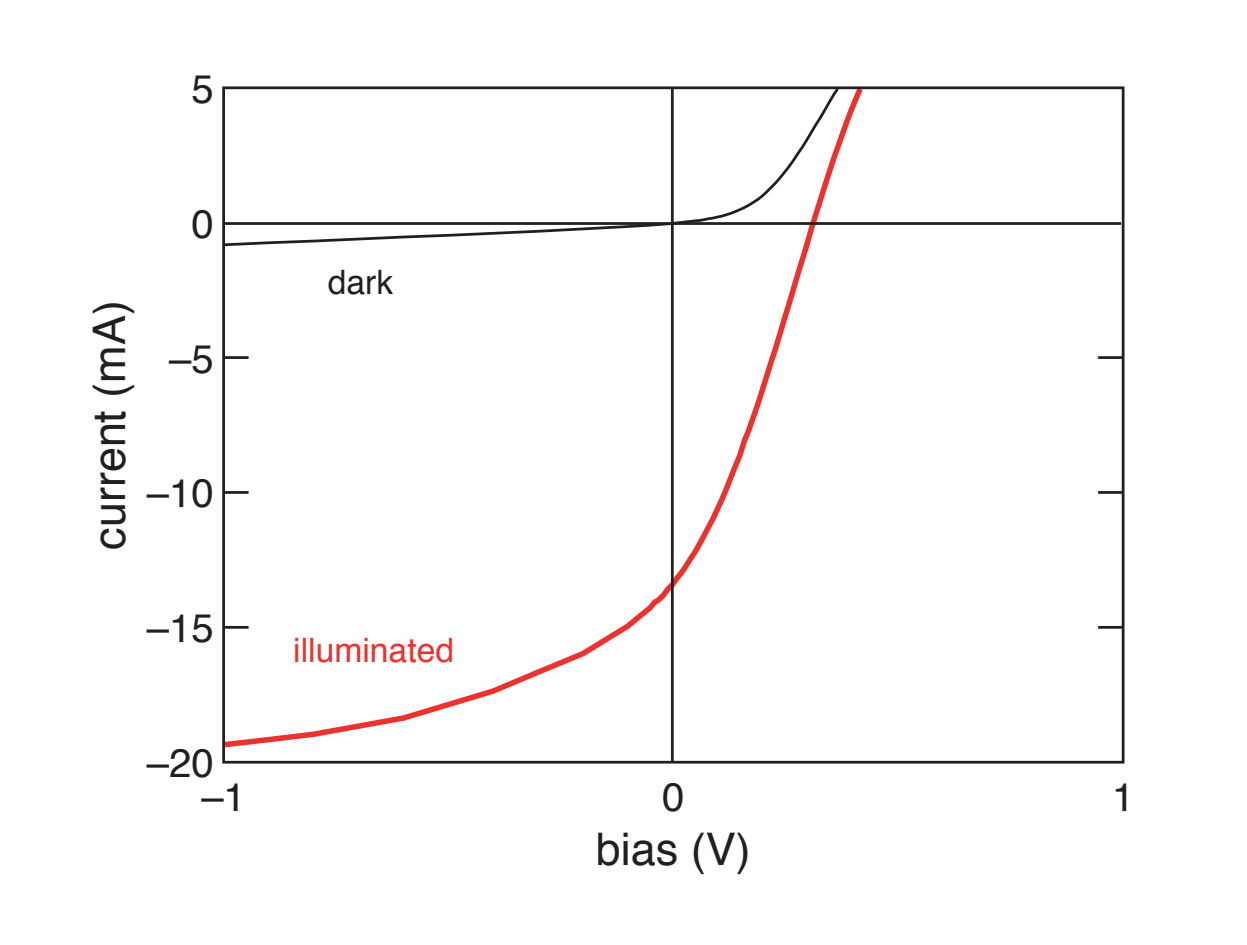


very preliminary photovoltaic cell



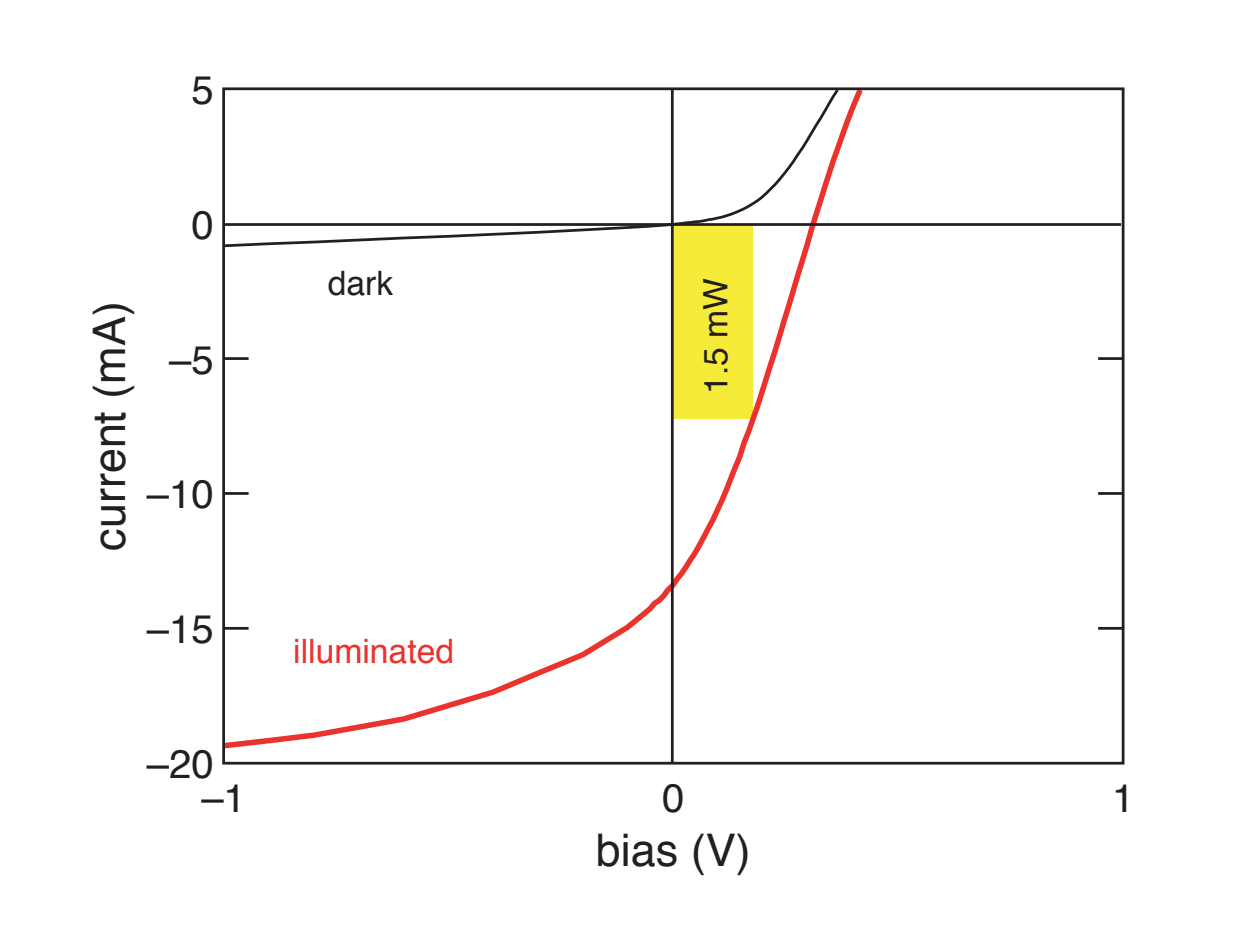
1 structure 2 OE properties 3 devices

very preliminary photovoltaic cell



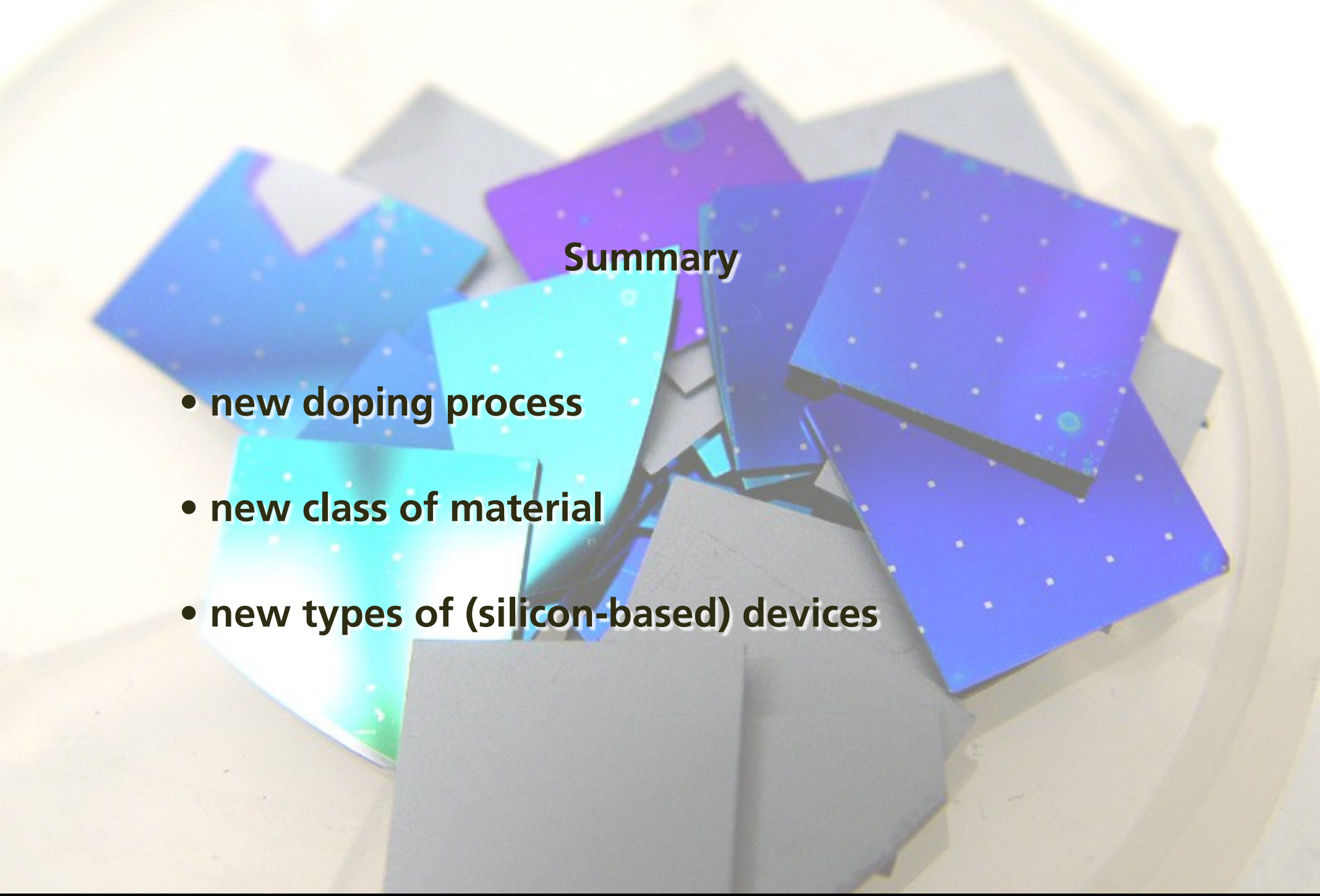
1 structure 2 OE properties 3 devices

1.5% efficiency, a good beginning



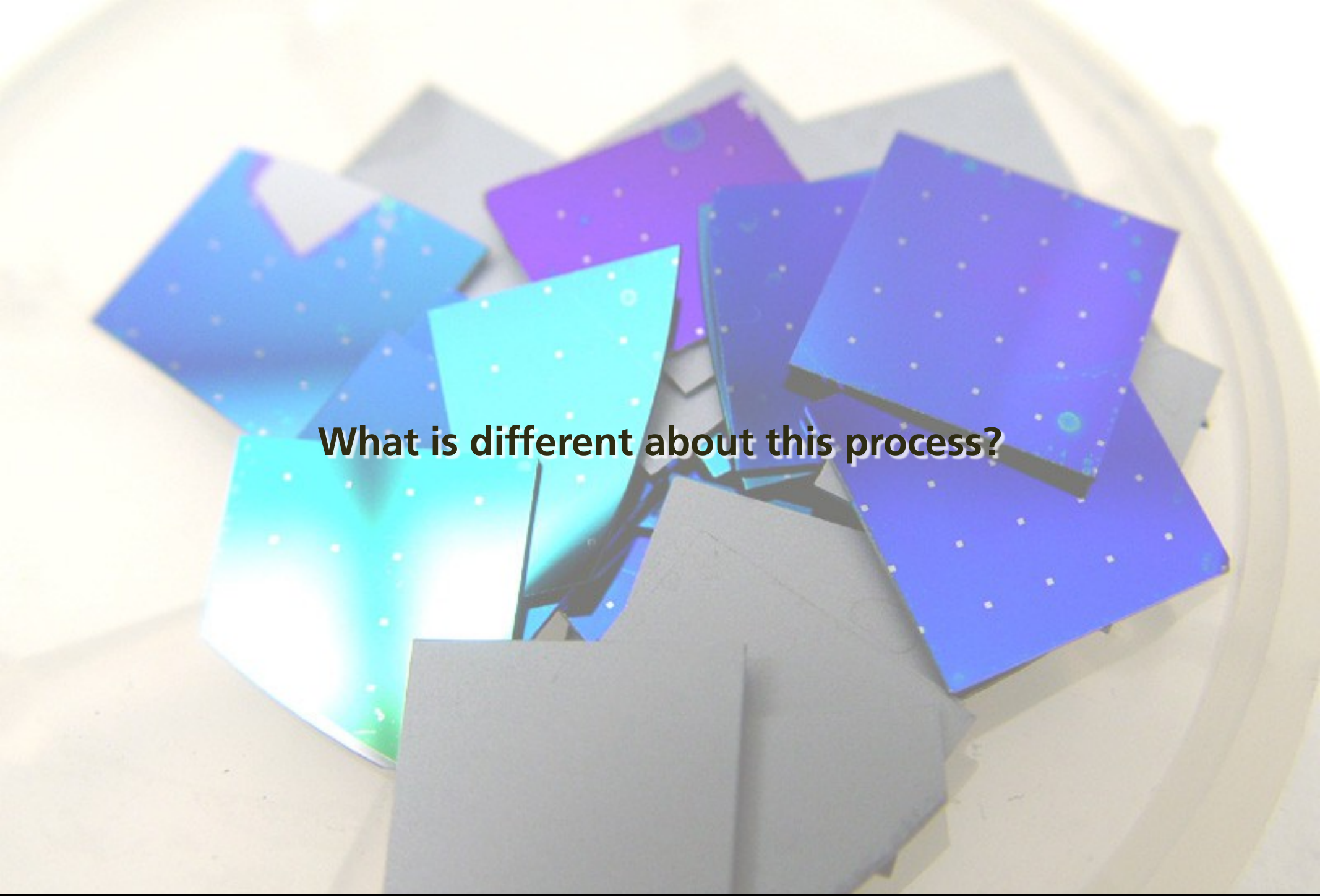
Things to keep in mind

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



Summary

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

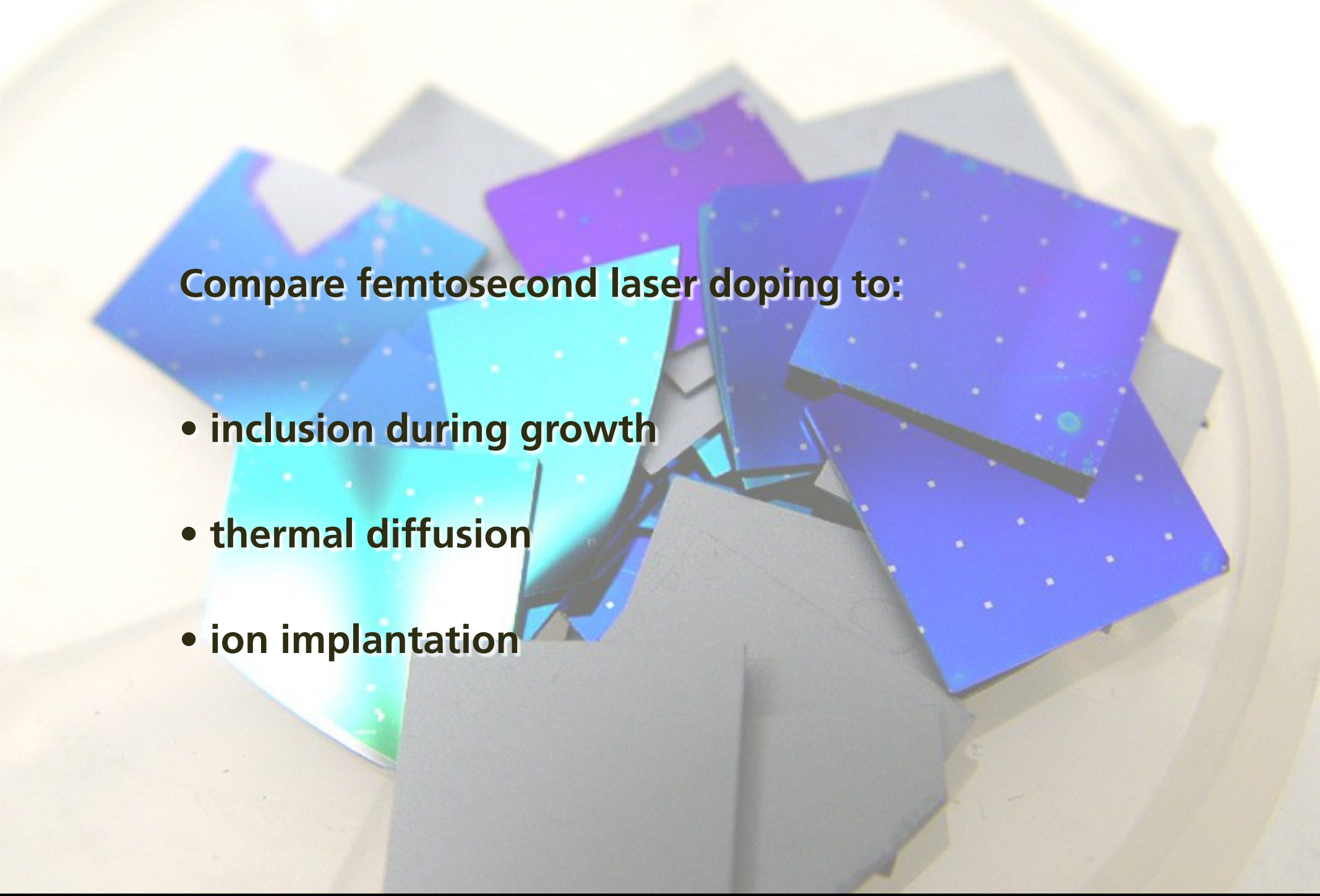


What is different about this process?

1 structure

2 OE properties

3 devices



Compare femtosecond laser doping to:

- inclusion during growth
- thermal diffusion
- ion implantation

Funding:

Army Research Office
DARPA
Department of Energy
NDSEG
National Science Foundation

for more information and a copy of this presentation:

http://mazur.harvard.edu

Follow me! **eric_mazur**

Google™

Google Search I'm Feeling Lucky

Google™

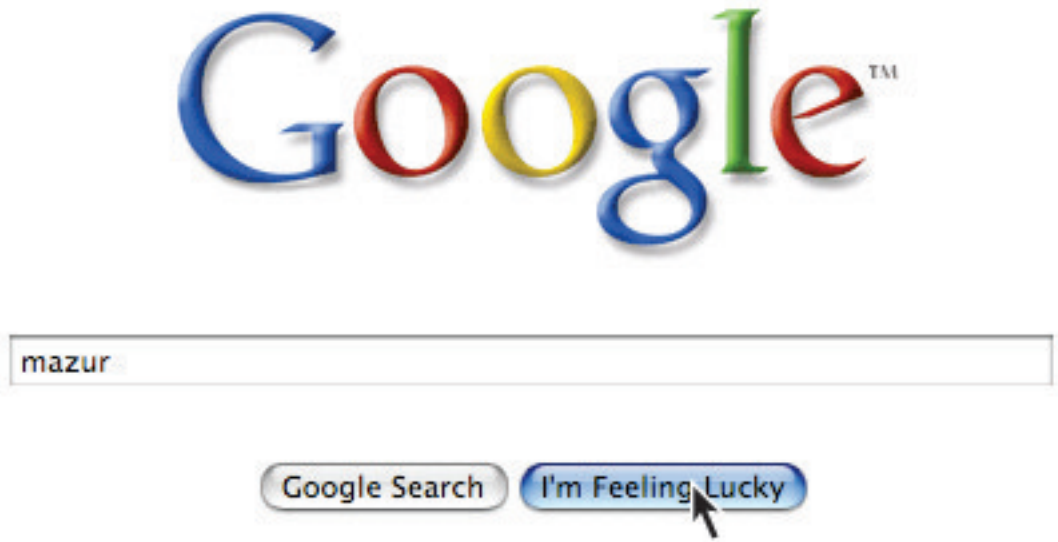
mazur

Google Search | I'm Feeling Lucky

Google™

mazur

Google Search | I'm Feeling Lucky


Google™
mazur
Google Search
I'm Feeling Lucky

Funding:

Army Research Office
DARPA
Department of Energy
NDSEG
National Science Foundation

for more information and a copy of this presentation:

http://mazur.harvard.edu

Follow me! **eric_mazur**