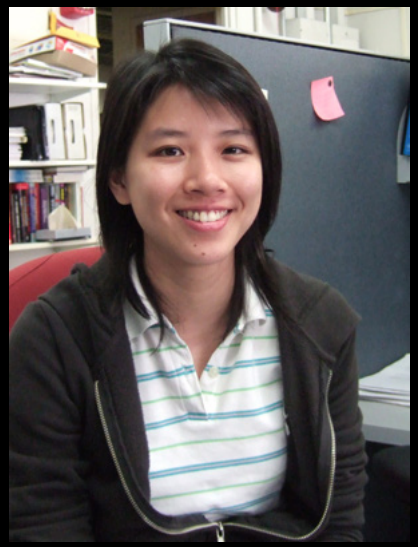
Laser-processing of semiconductors and (some) applications

HUCE Lunch Seminar
Cambridge, MA, 31 January 2014

Renee Sher



Yu-Ting Lin

Kasey Philips

Ben Franta

eric_mazur

and also....

Marc Winkler
Eric Diebold
Haifei Albert Zhang
Dr. Brian Tull
Dr. Jim Carey (SiOnyx)
Prof. Tsing-Hua Her (UNC Charlotte)
Dr. Shrenik Deliwala
Dr. Richard Finlay
Dr. Michael Sheehy
Dr. Claudia Wu
Dr. Rebecca Younkin
Prof. Catherine Crouch (Swarthmore)
Prof. Mengyan Shen (Lowell U)
Prof. Li Zhao (Fudan U)

Dr. Elizabeth Landis
Dr. John Chervinsky

Prof. Alan Aspuru-Guzik
Prof. Michael Aziz
Prof. Michael Brenner
Prof. Cynthia Friend
Prof. Howard Stone

Dr. Martin Pralle (SiOnyx)
and everyone else at SiOnyx…

Prof. Tonio Buonassisi (MIT)
Prof. Silvija Gradecak (MIT)
Prof. Jeff Grossman (MIT)
Dr. Bonna Newman (MIT)
Joe Sullivan (MIT)
Matthew Smith (MIT)

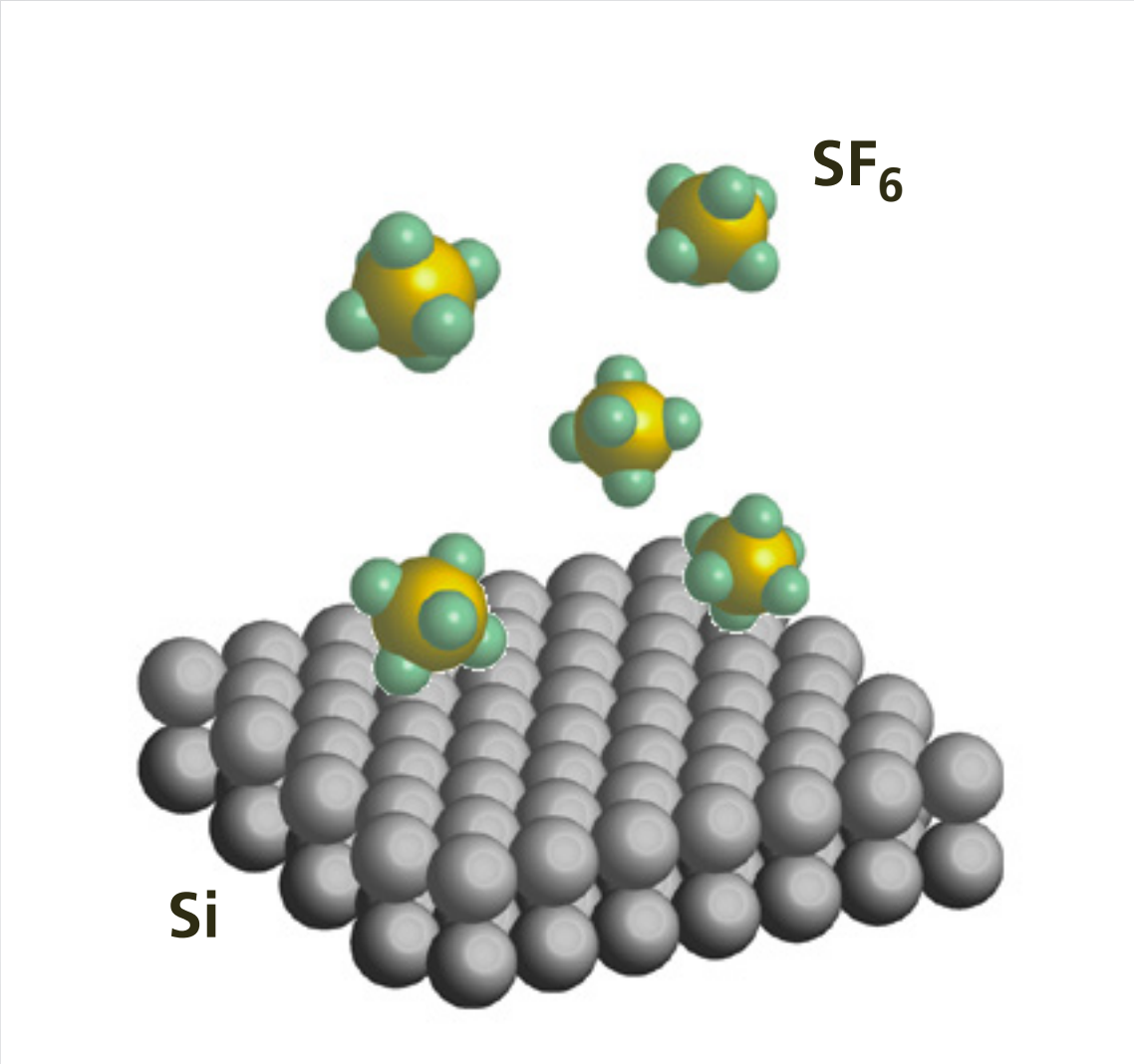
Prof. Augustinus Asenbaum (Vienna)

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

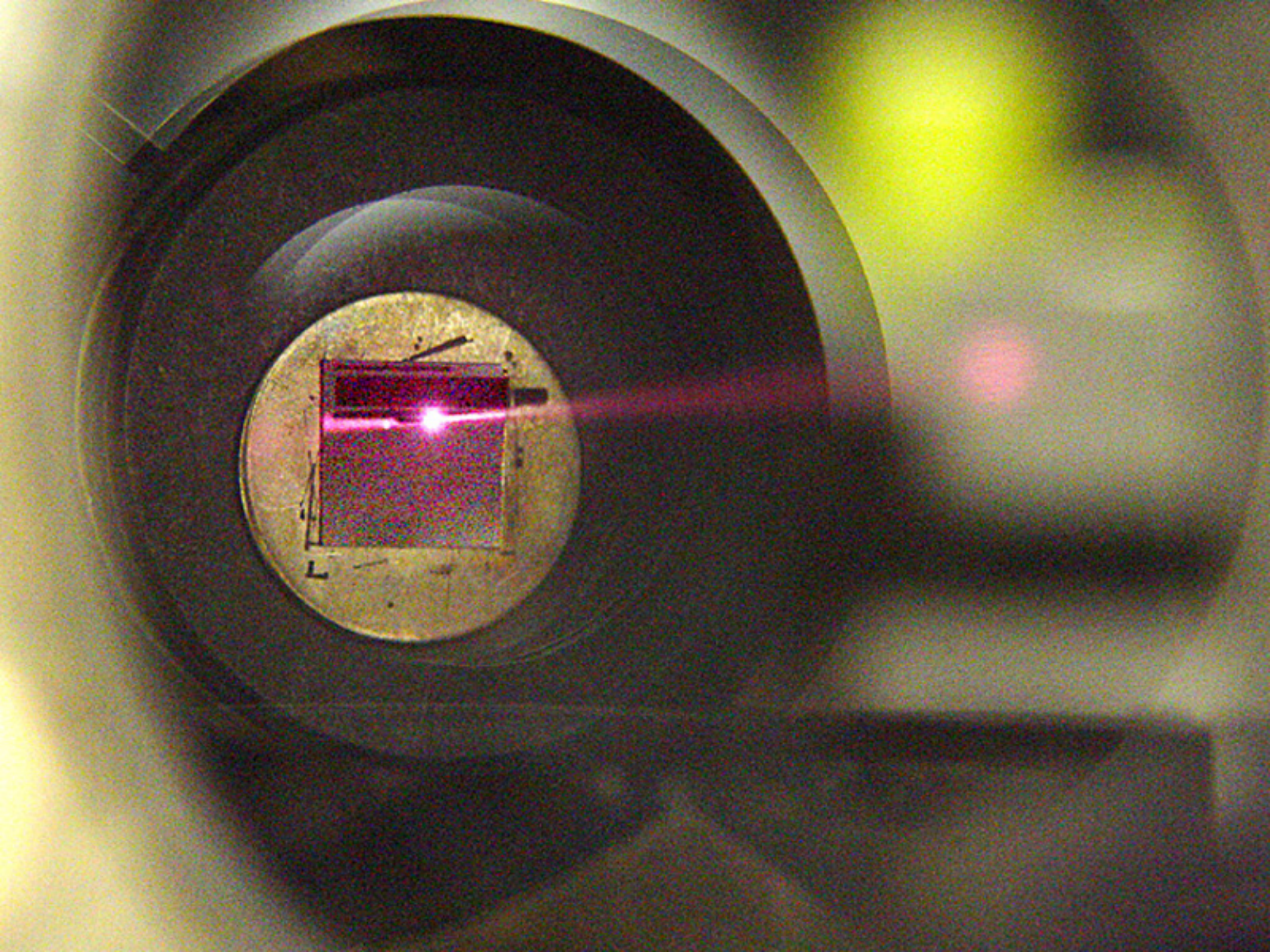
Dr. Richard Farrell (RMD)
Dr. Arieh Karger (RMD)
Dr. Richard Meyers (RMD)

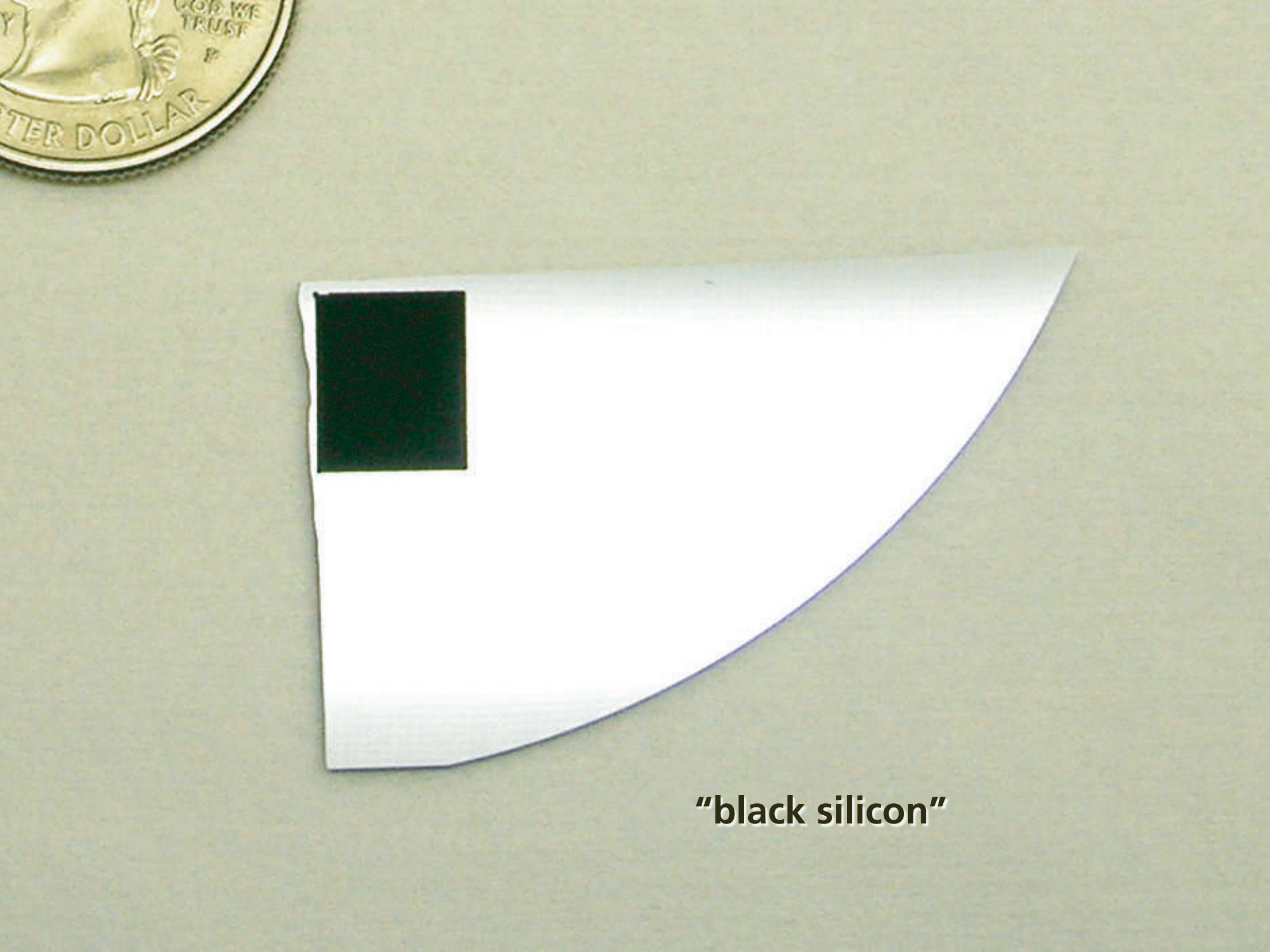
Dr. Pat Maloney (NVSED)

Dr. Jeffrey Warrander (ARDEC)

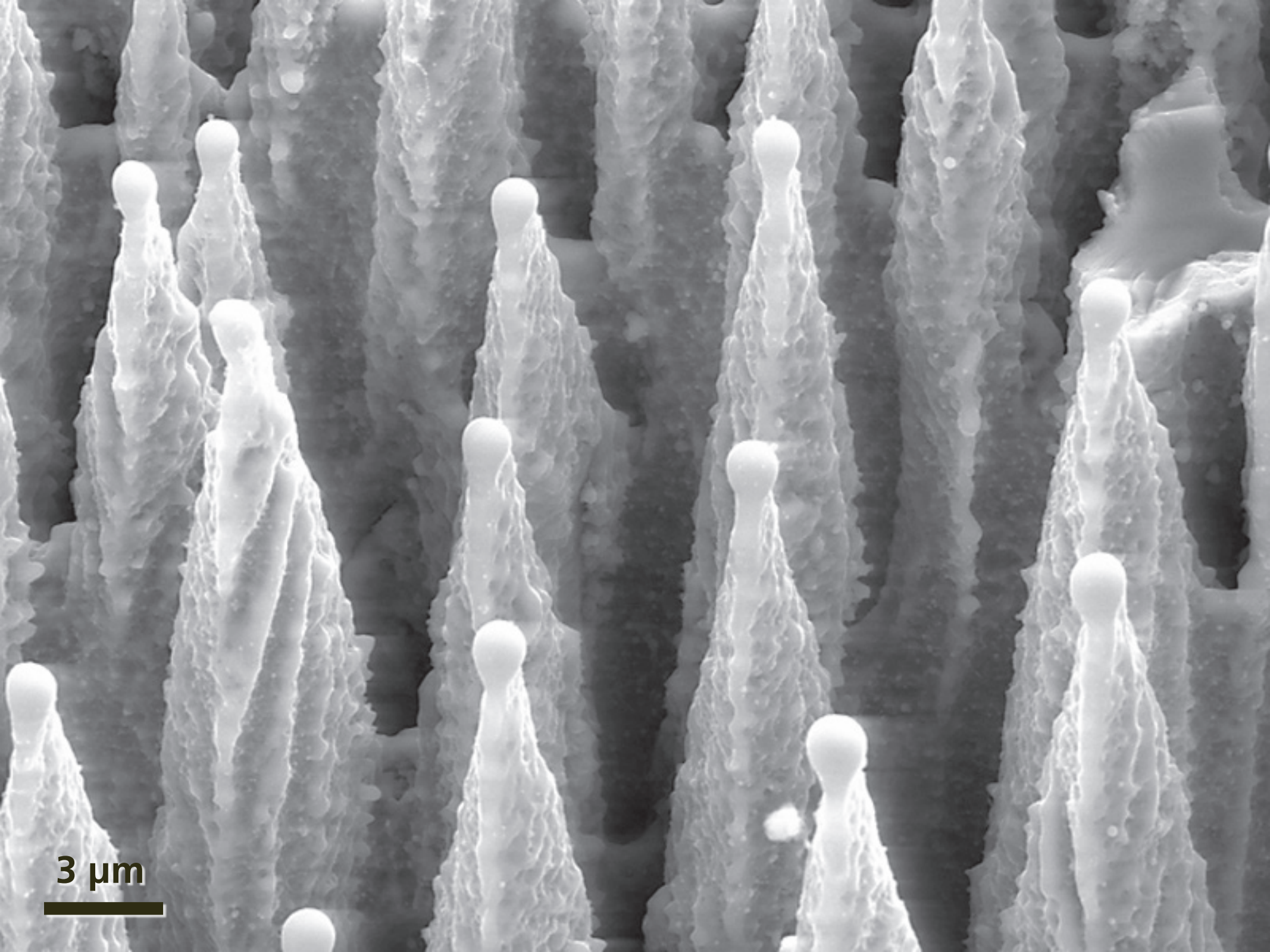


irradiate with 100-fs 10 kJ/m^2 pulses

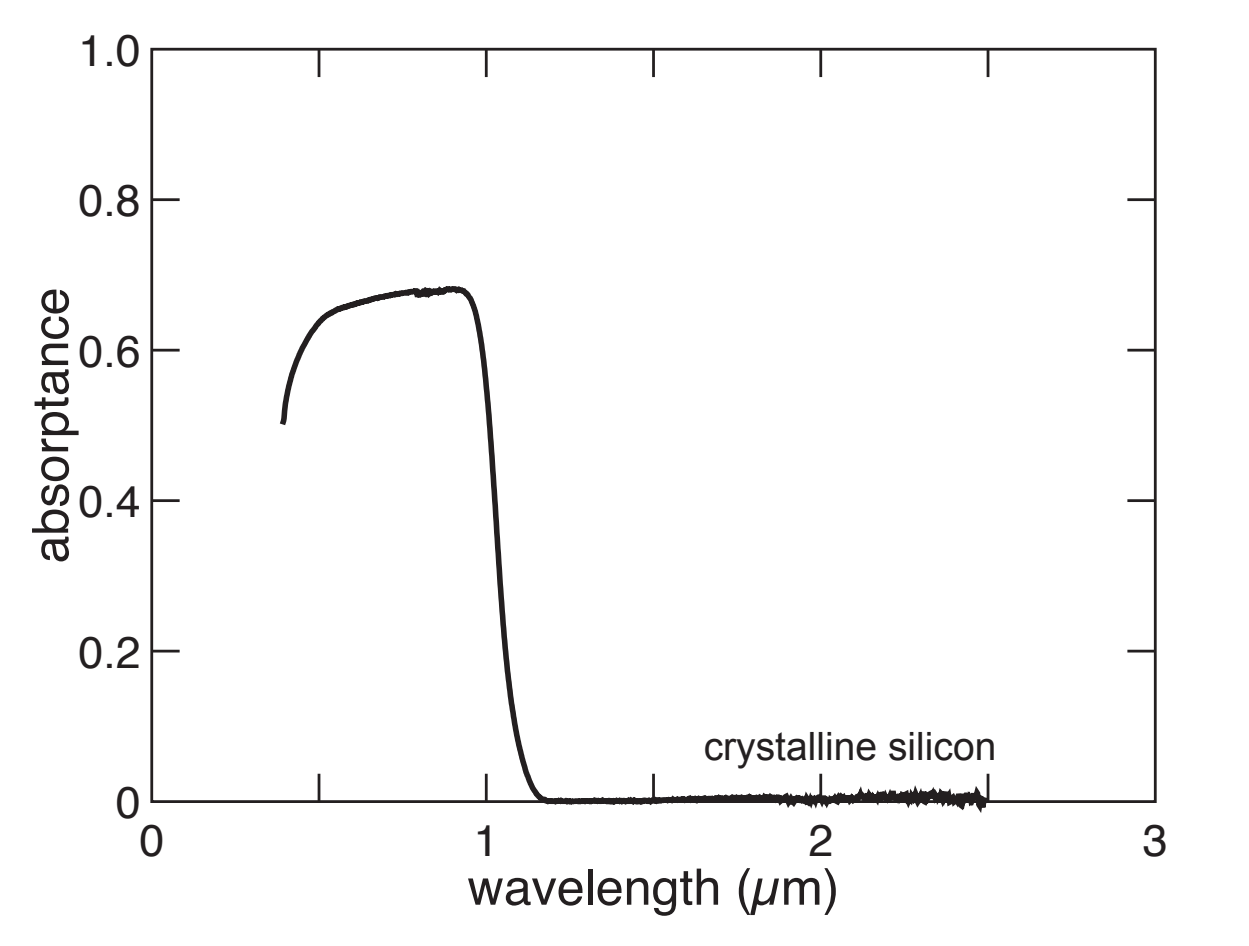




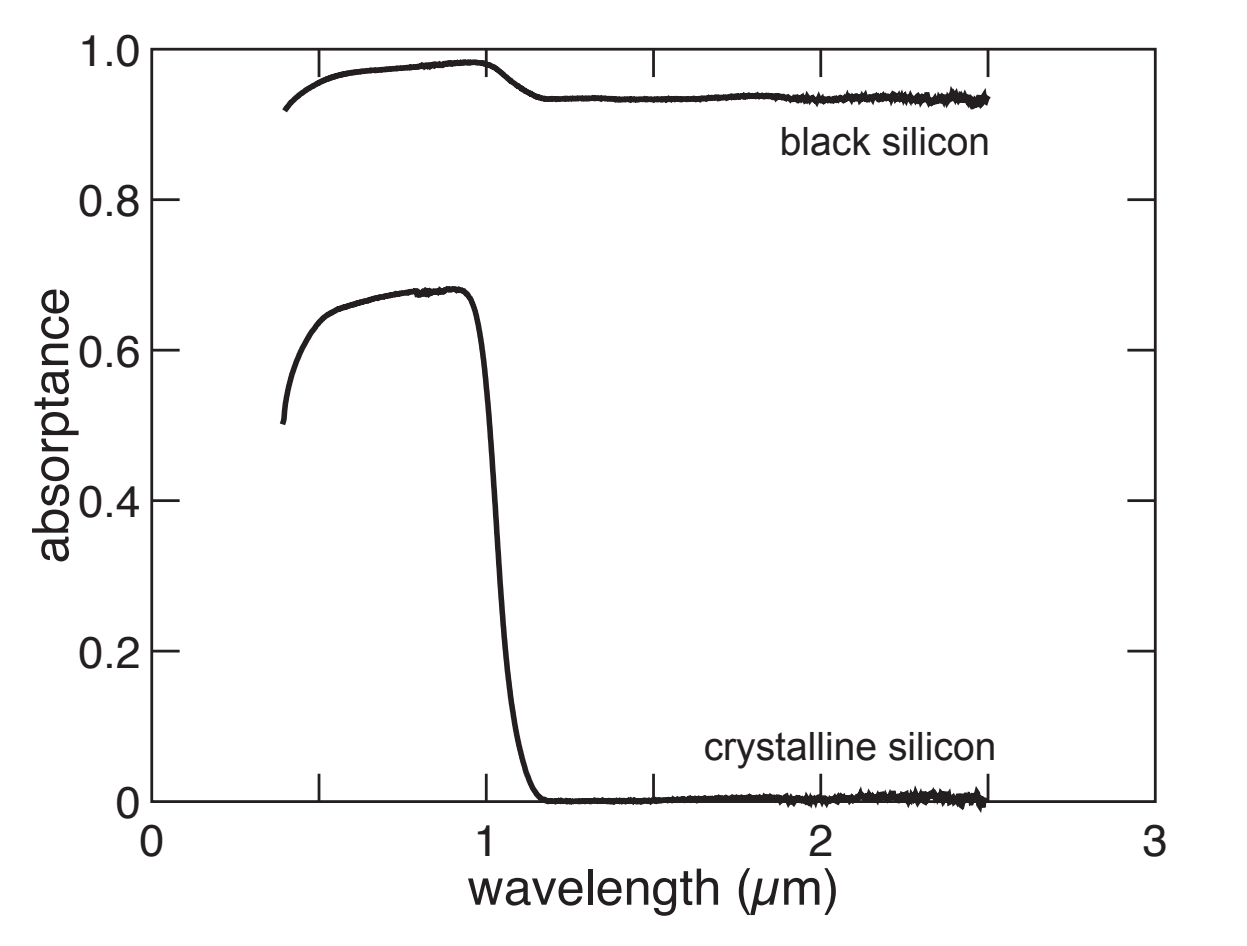
“black silicon”

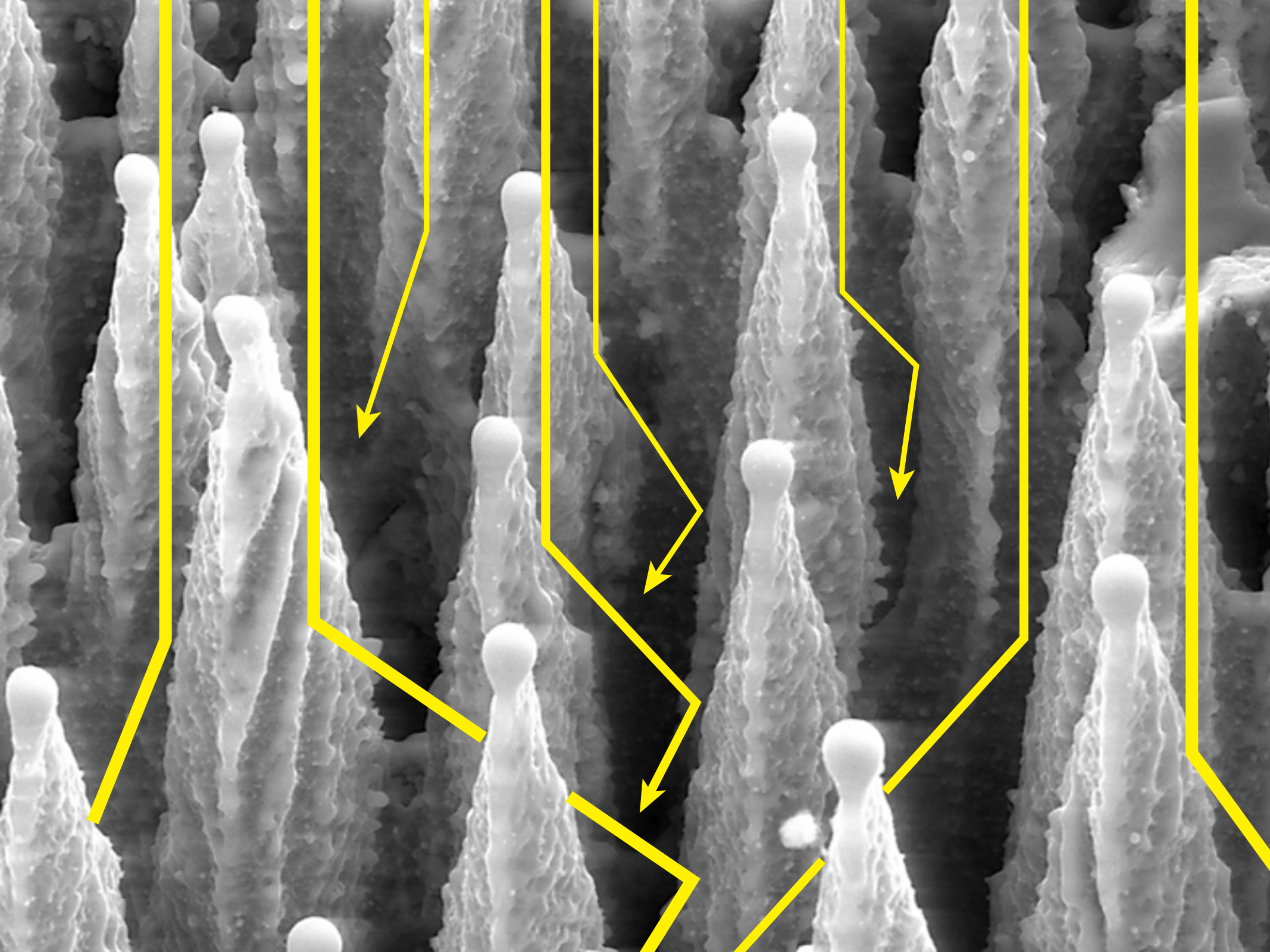

3 µm

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

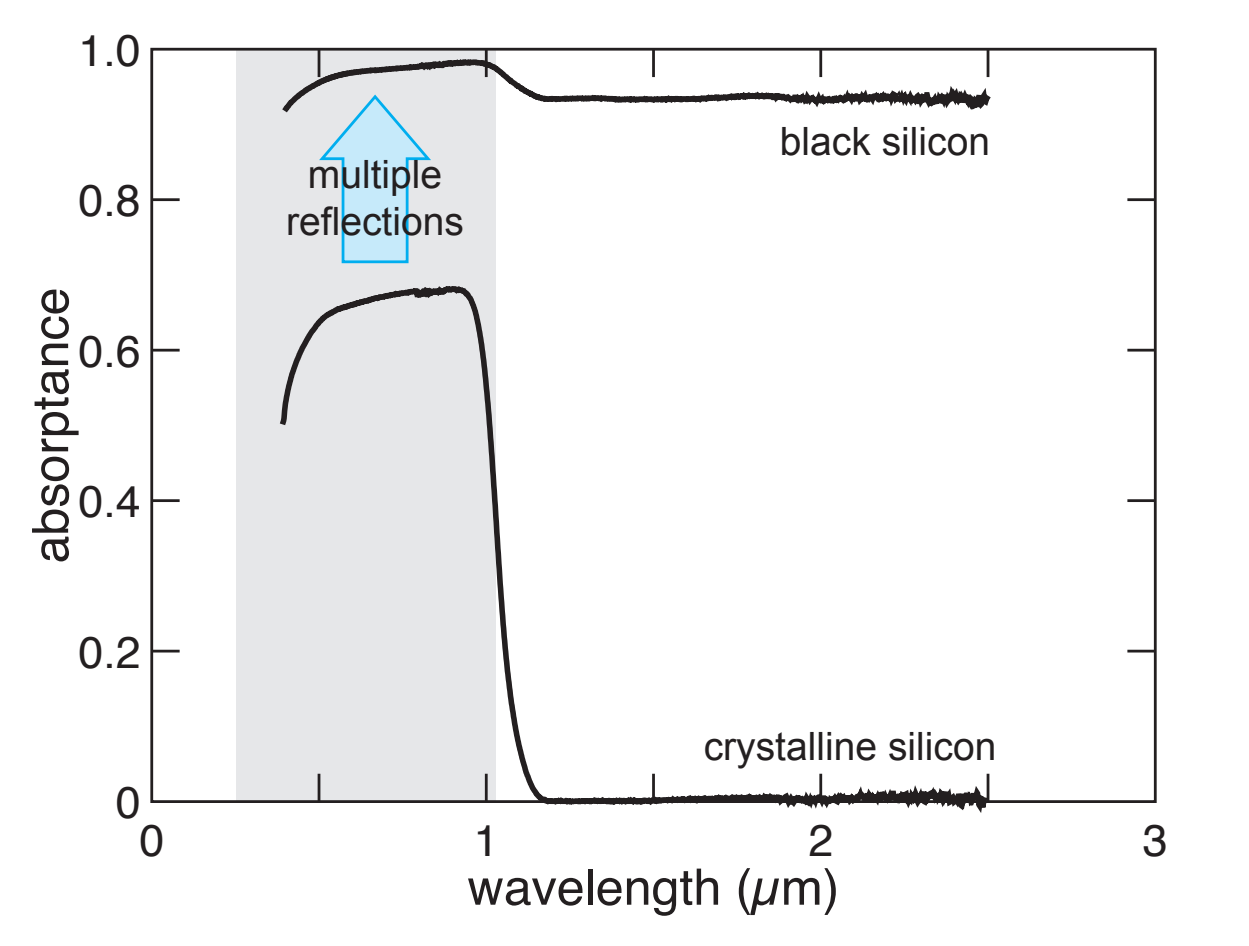


absorptance ($1 - R_{int} - T_{int}$)

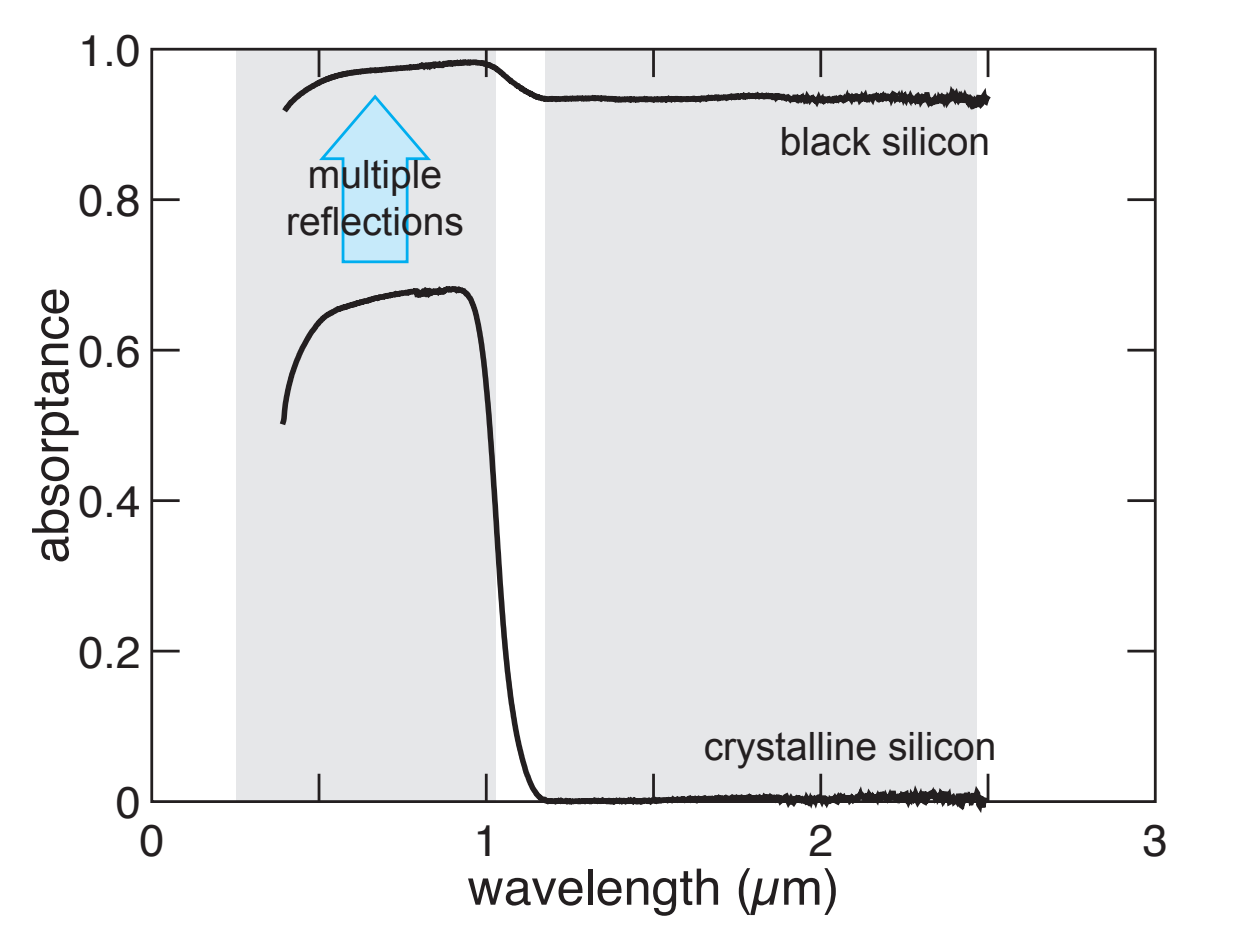




absorptance ($1 - R_{int} - T_{int}$)



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



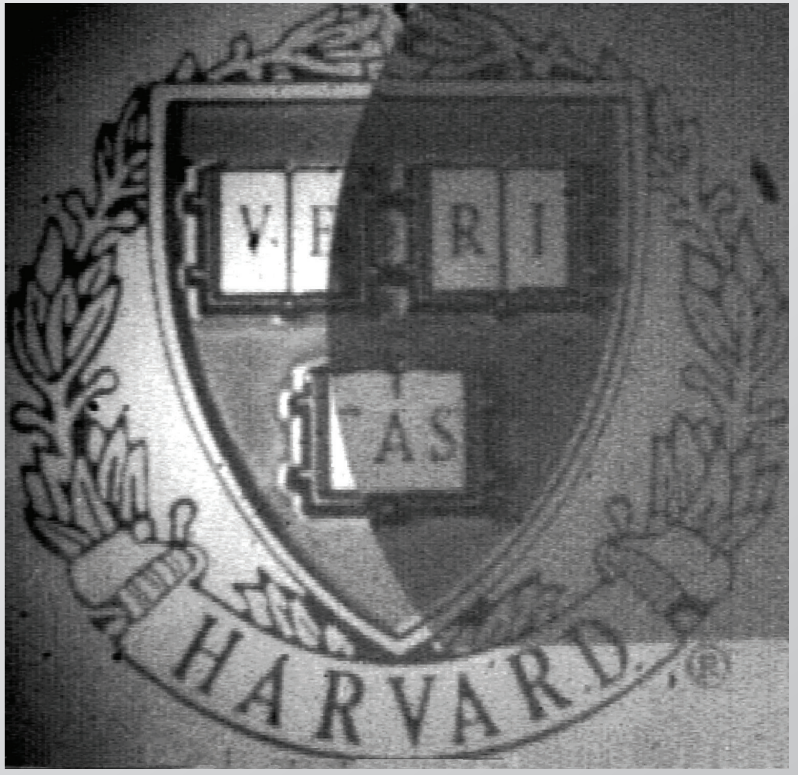
silicon transparent in IR

visible

silicon transparent in IR

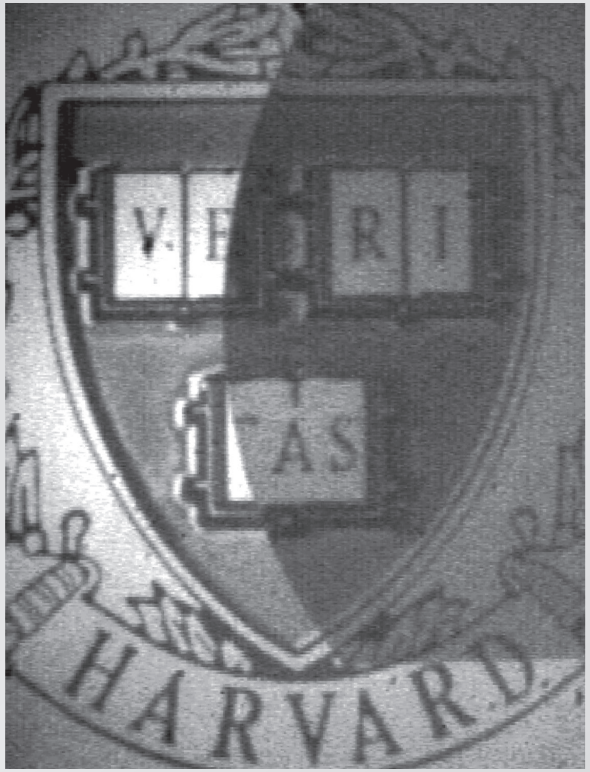
visible

IR

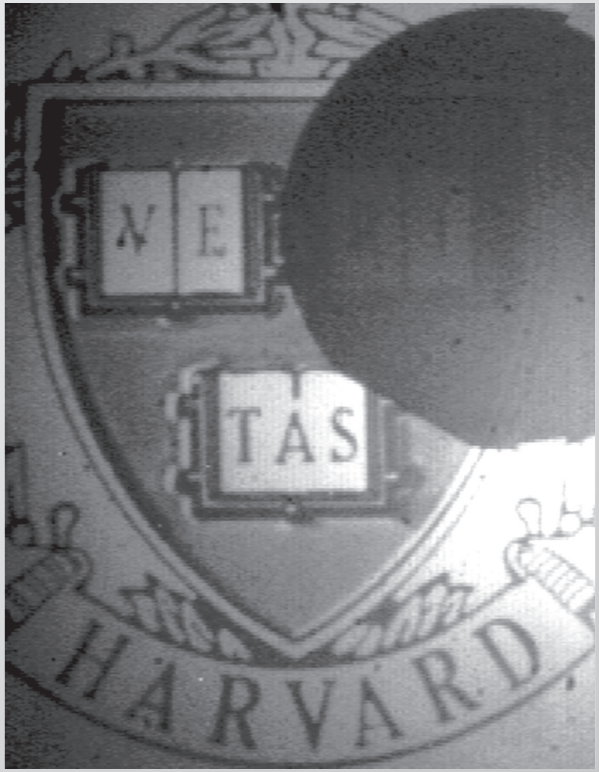


roughening doesn’t change IR transmission…

polished

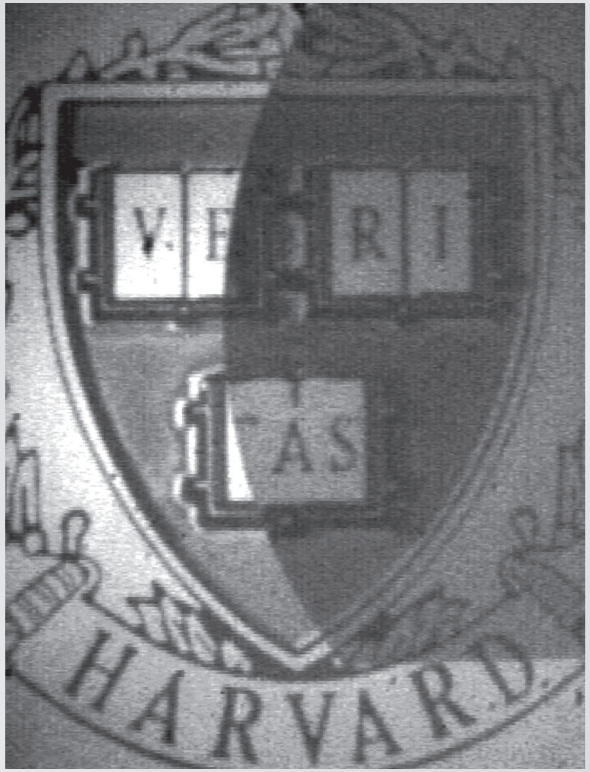


unpolished

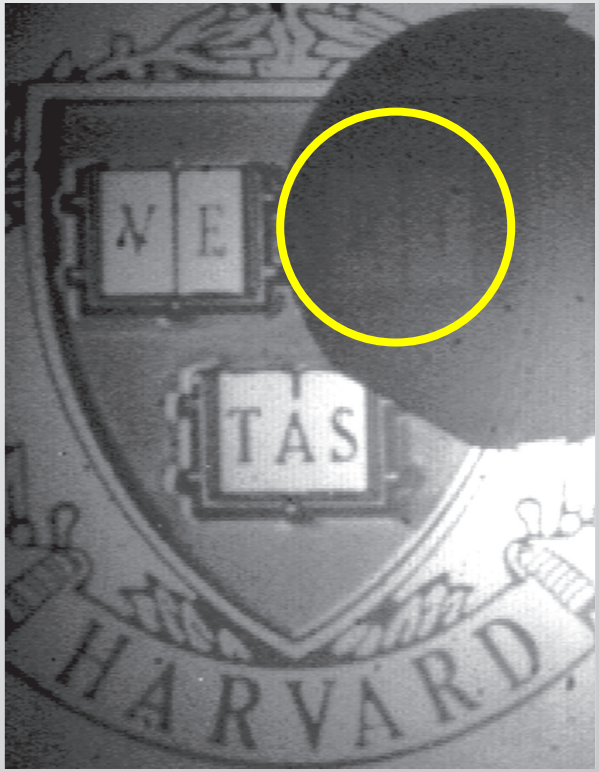


roughening doesn't change IR transmission…

polished

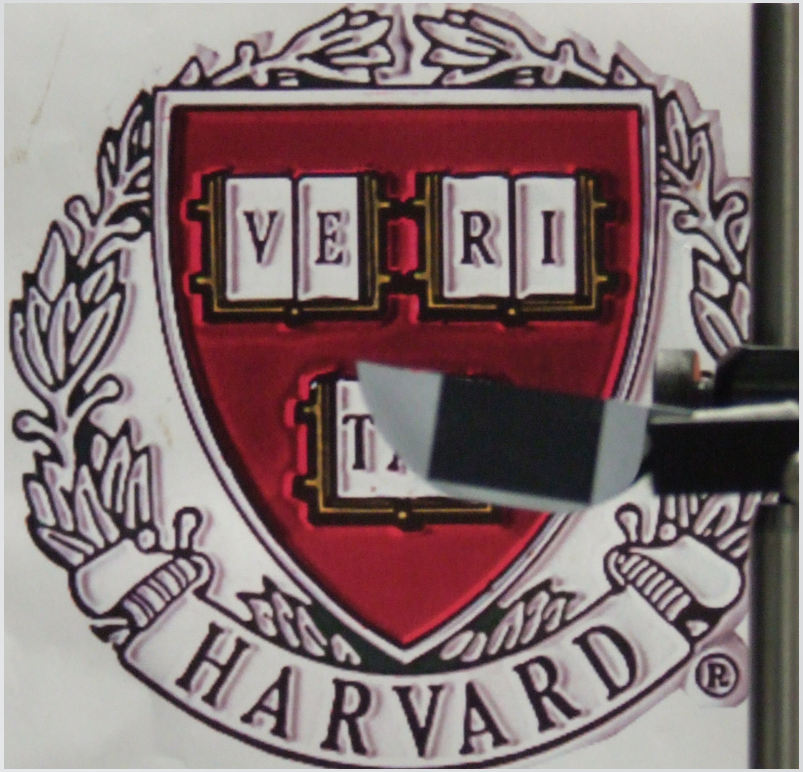


unpolished

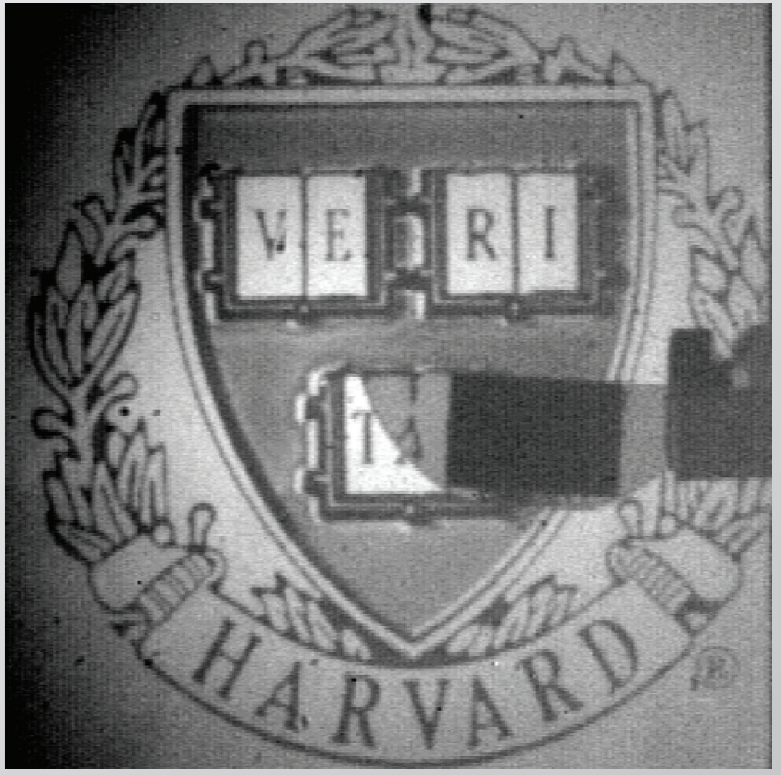


…but black silicon blocks IR completely

visible



IR



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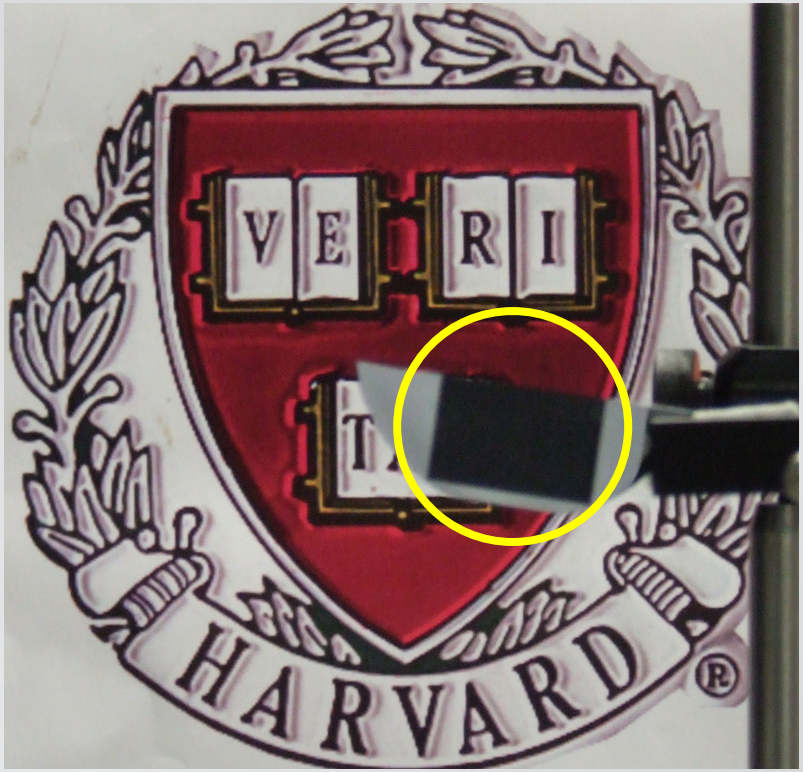
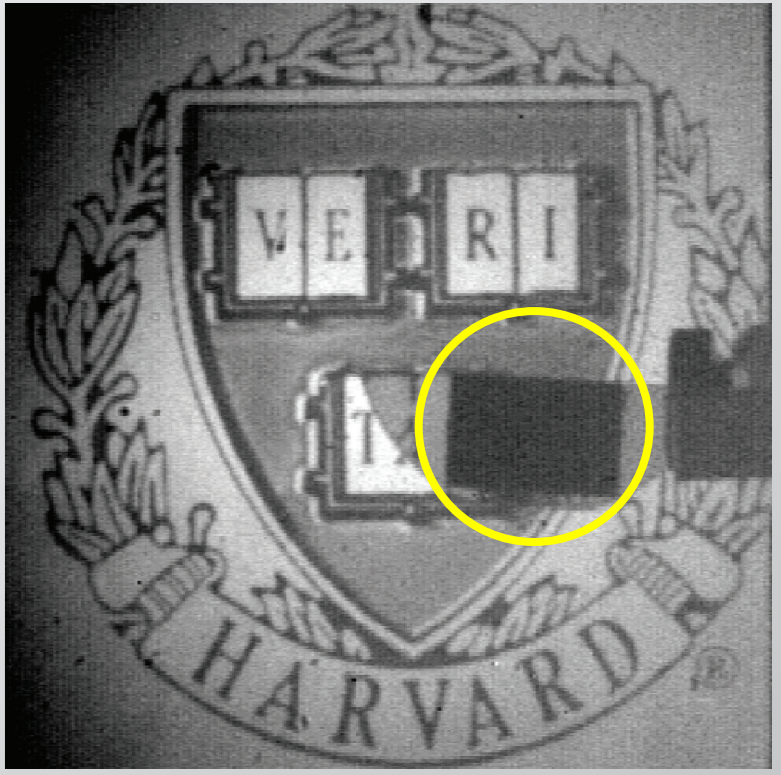
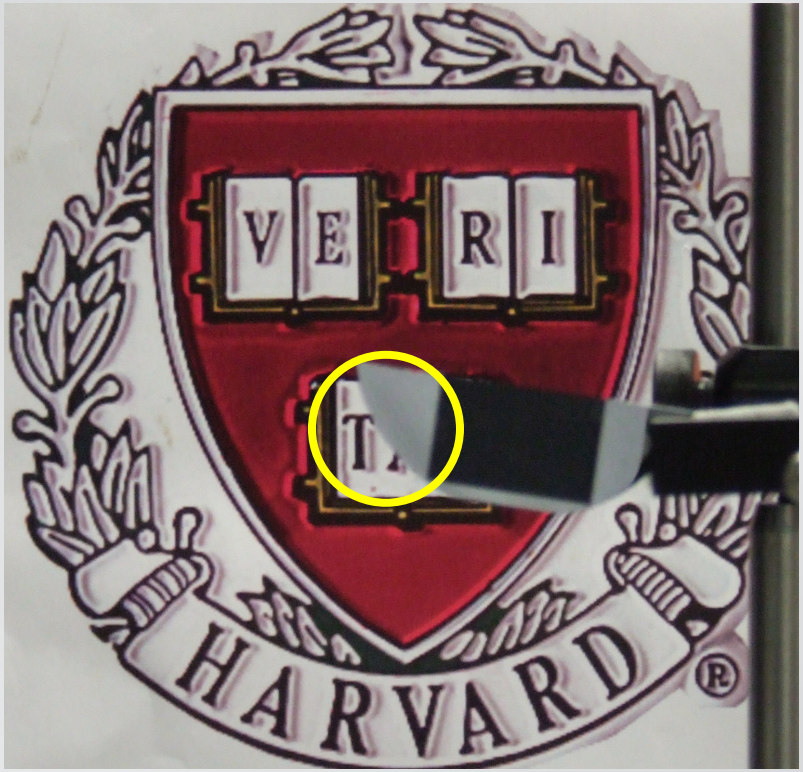


IR

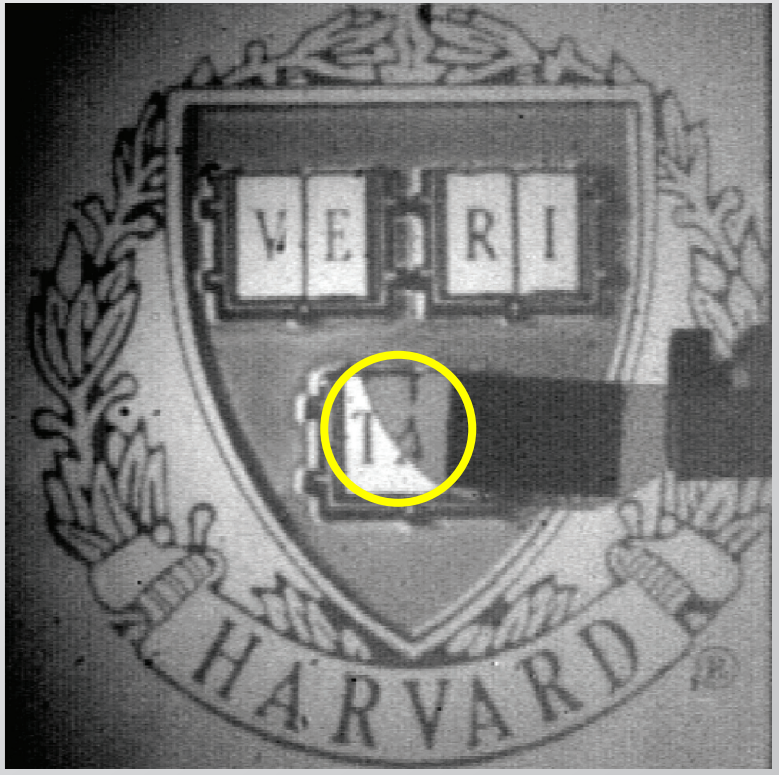


black silicon completely black in IR

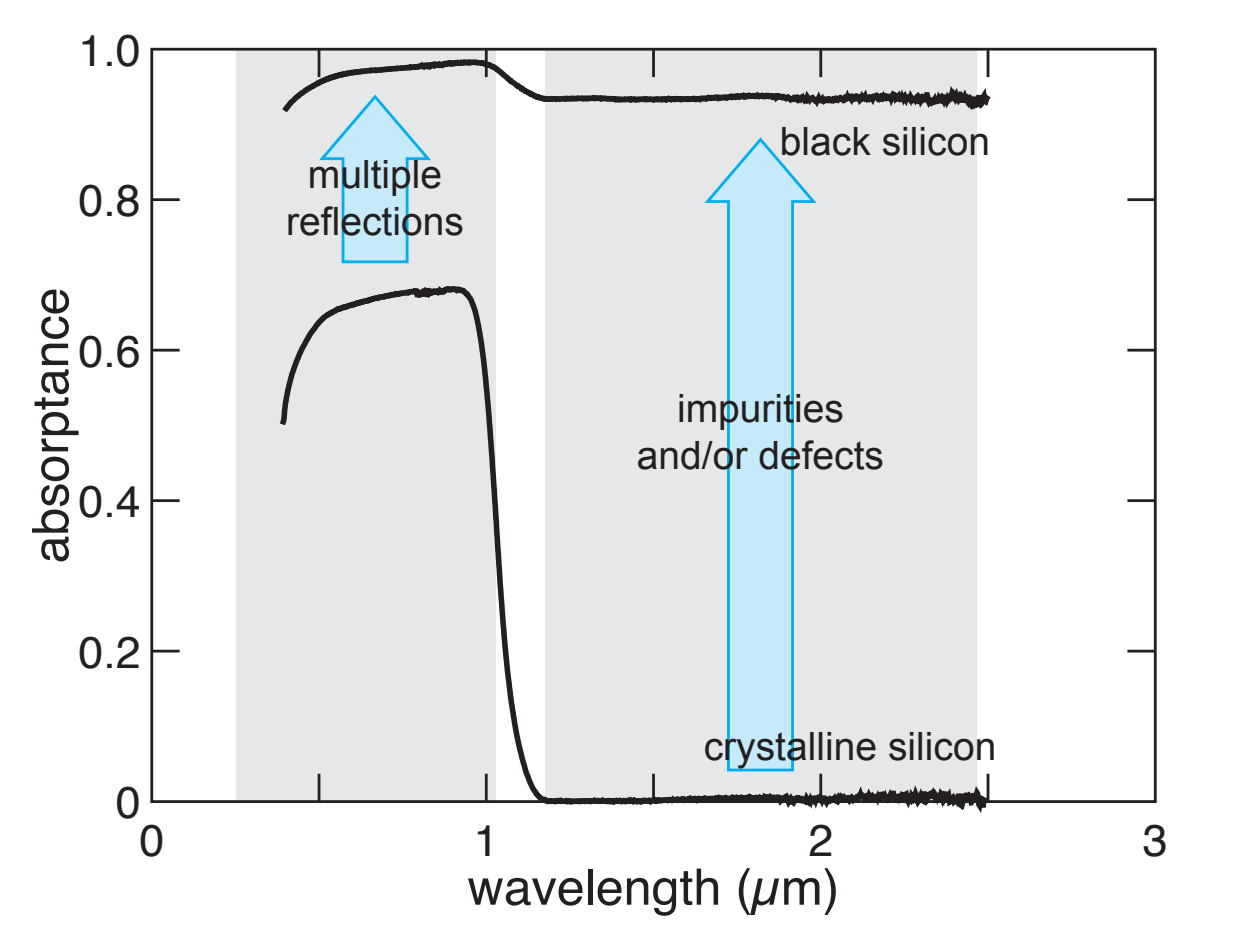
visible

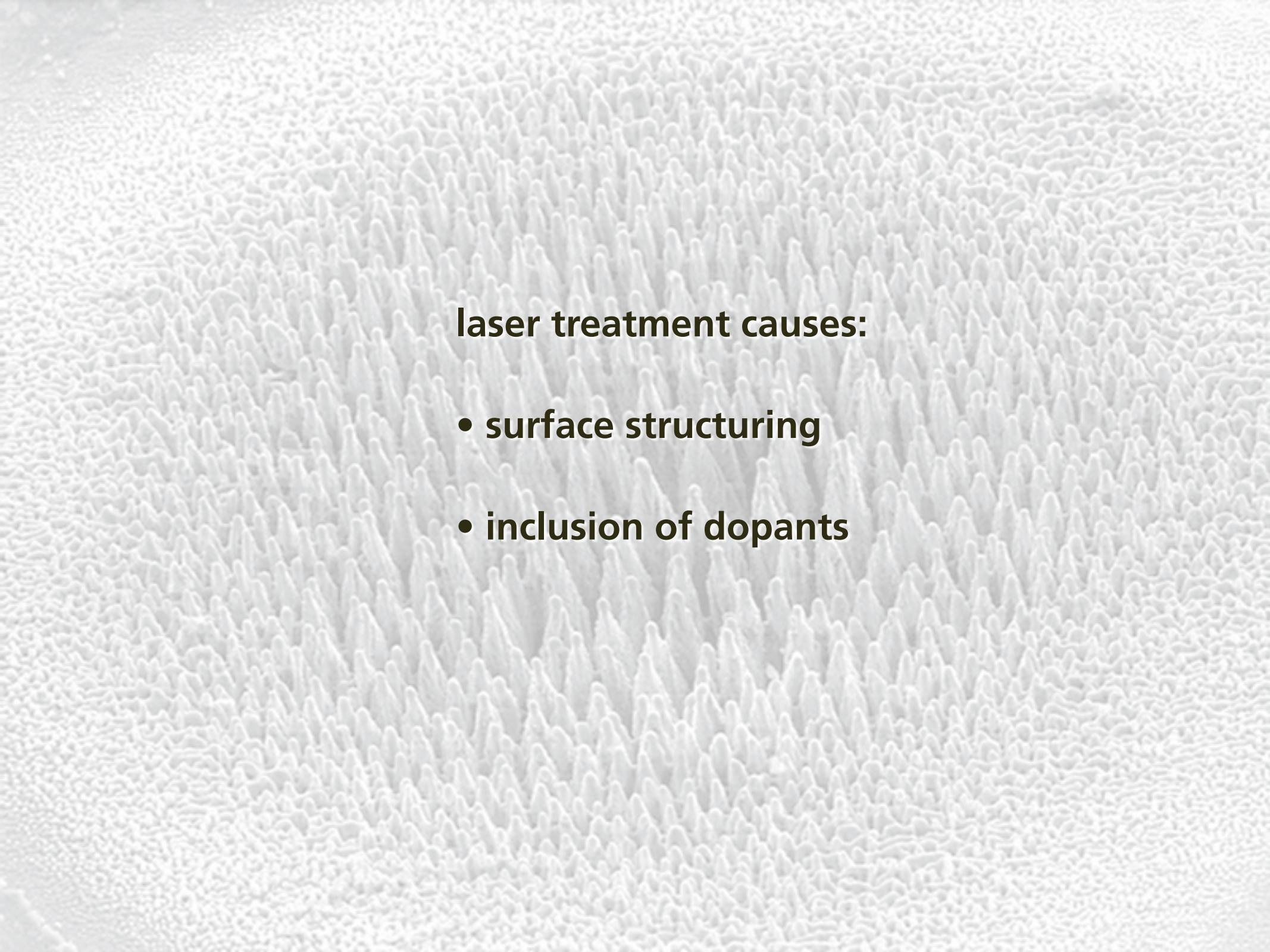


IR



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





laser treatment causes:

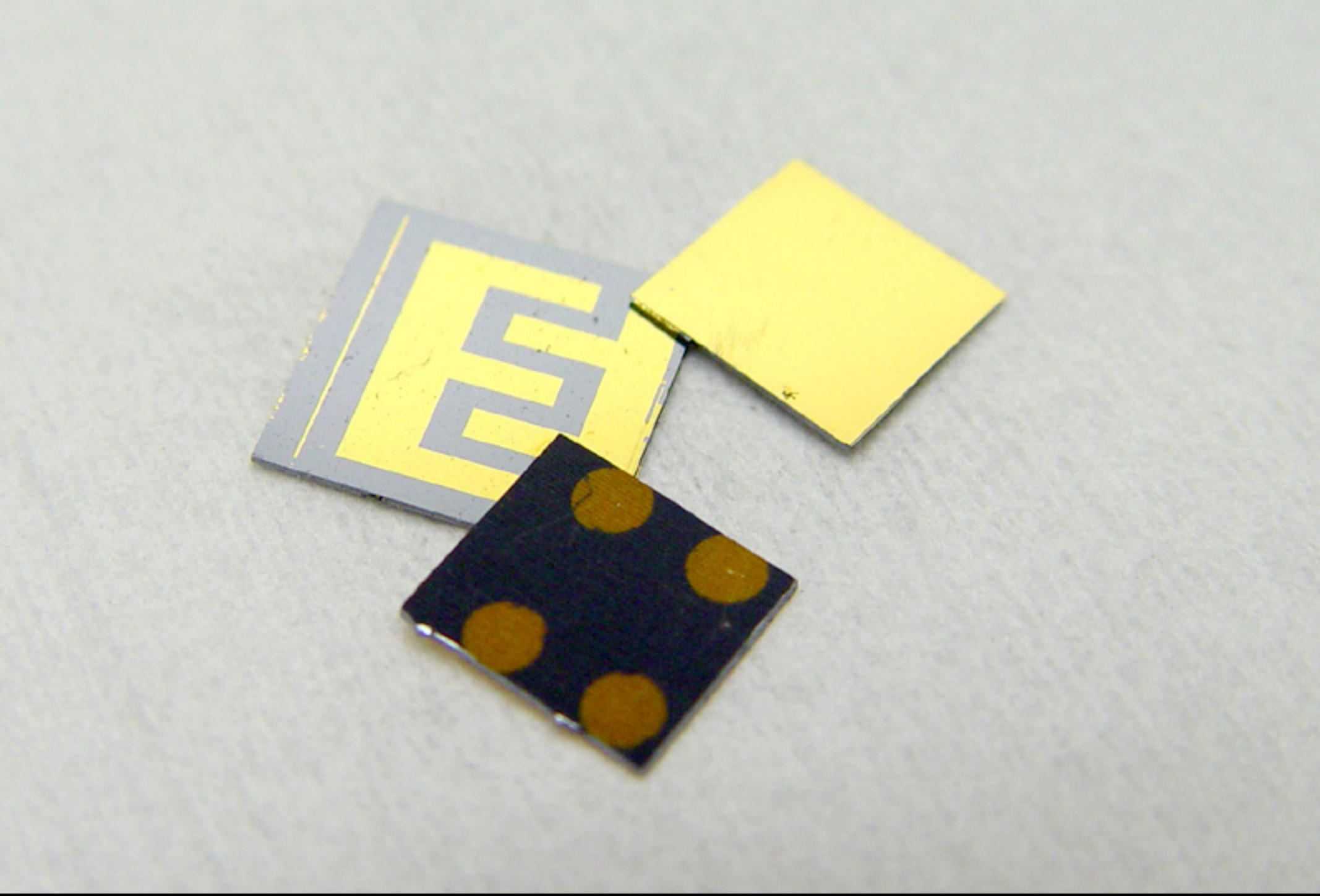
- **surface structuring**
- **inclusion of dopants**

black silicon “flavors”

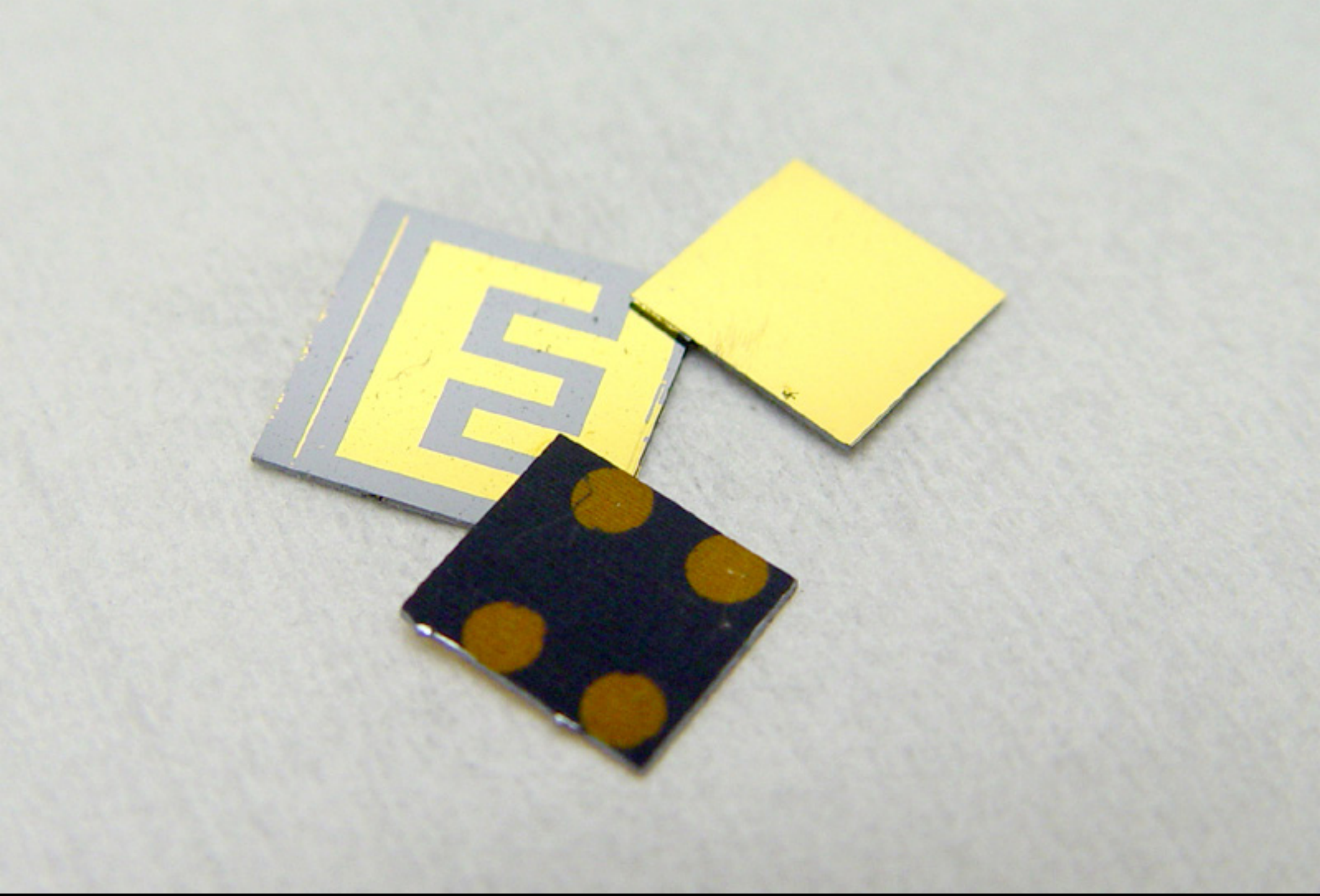
	surface structure	doping
reactive ion etching		
fs laser processing		
ion implantation		

black silicon “flavors”

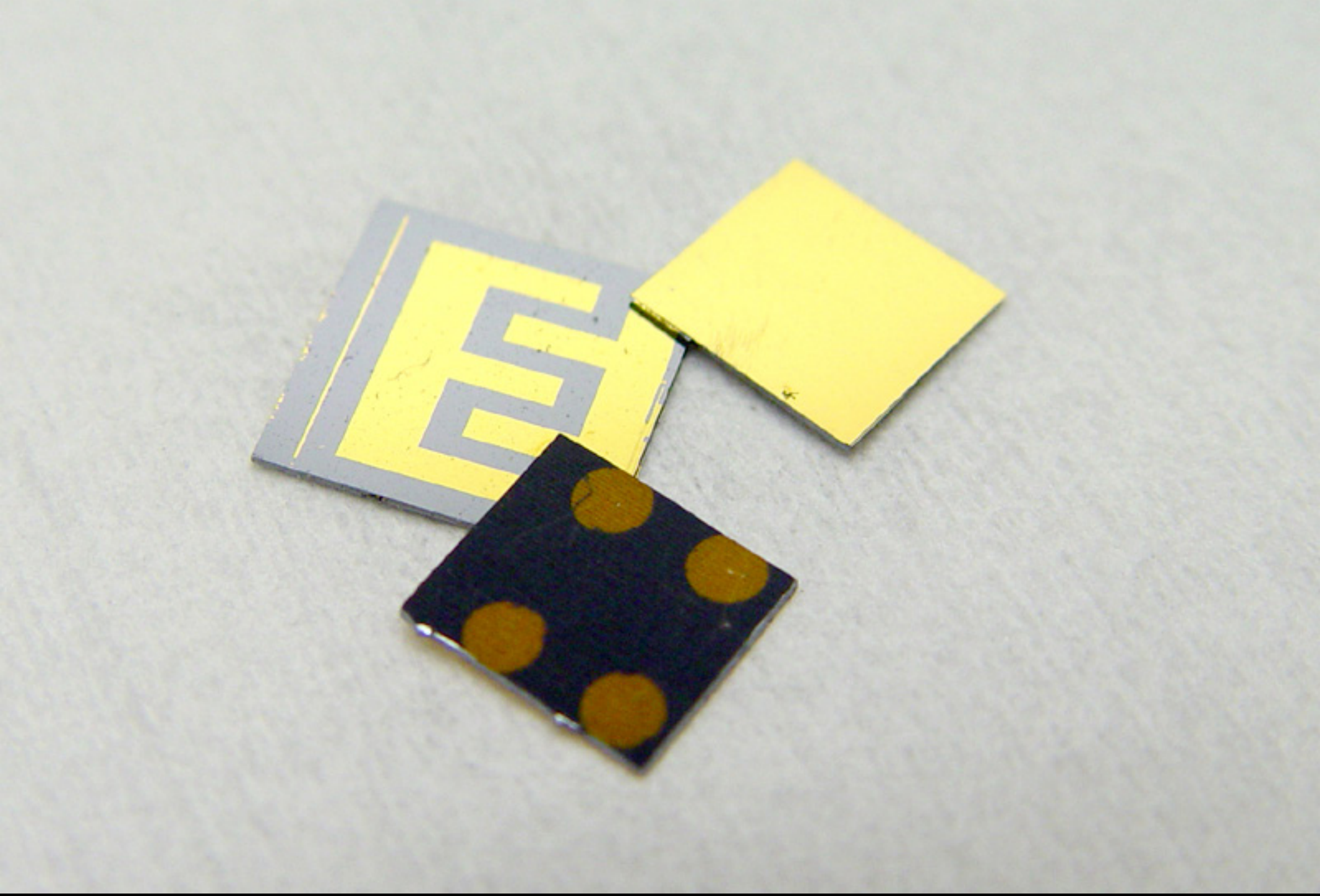
	surface structure	doping
reactive ion etching	✓	✗
fs laser processing	✓	✓
ion implantation	✗	✓



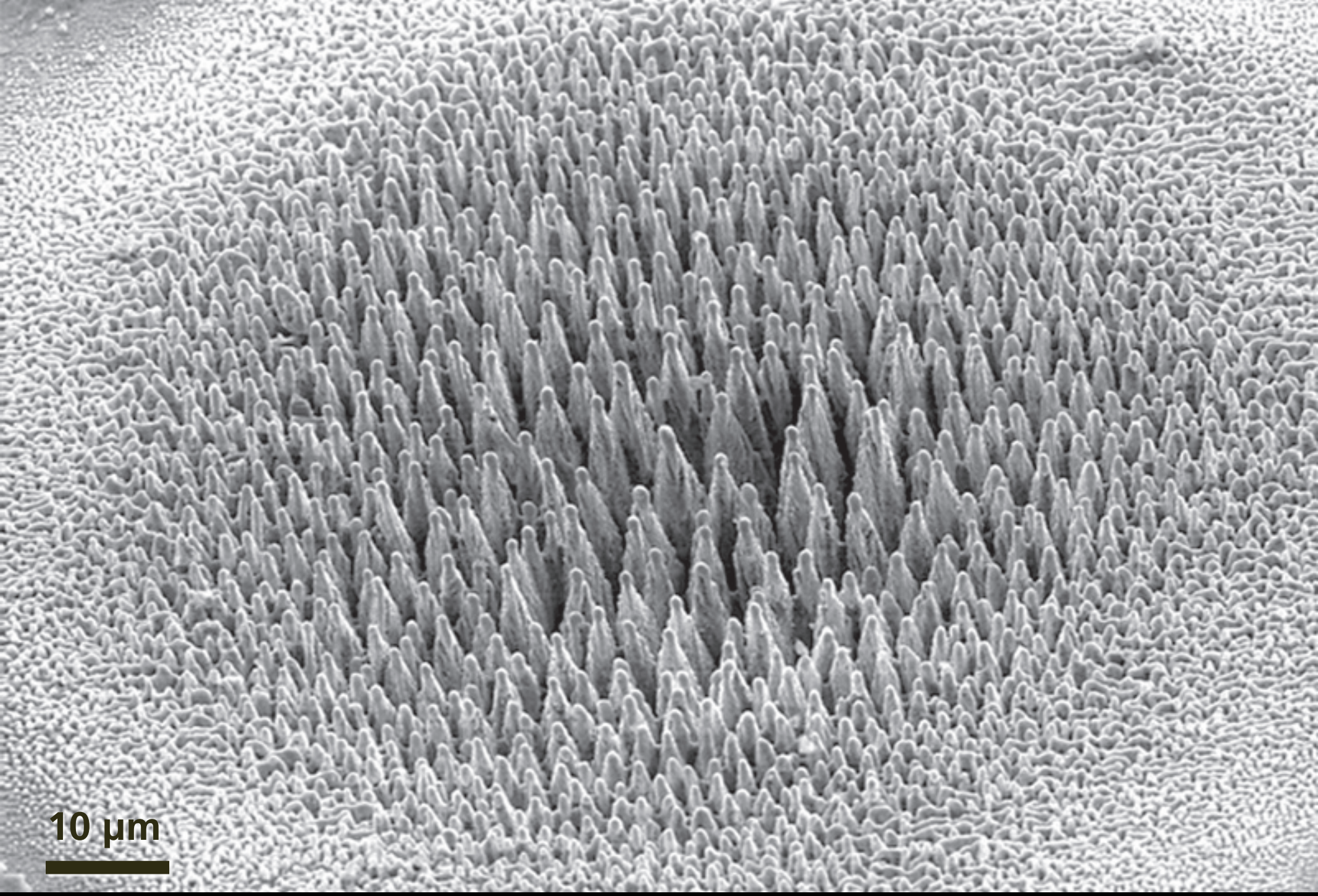
1 properties



1 properties 2 intermediate band



1 properties 2 intermediate band 3 devices



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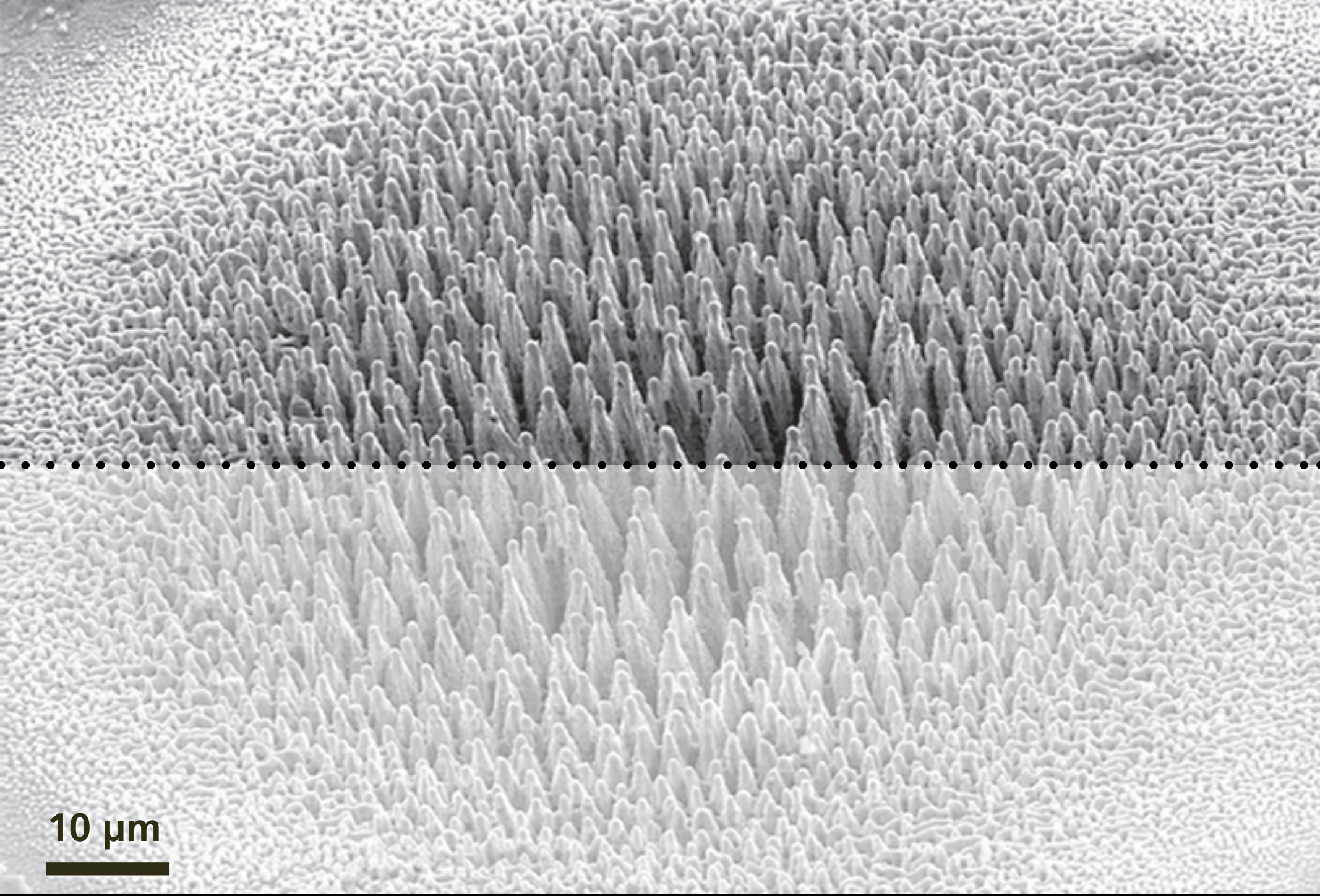

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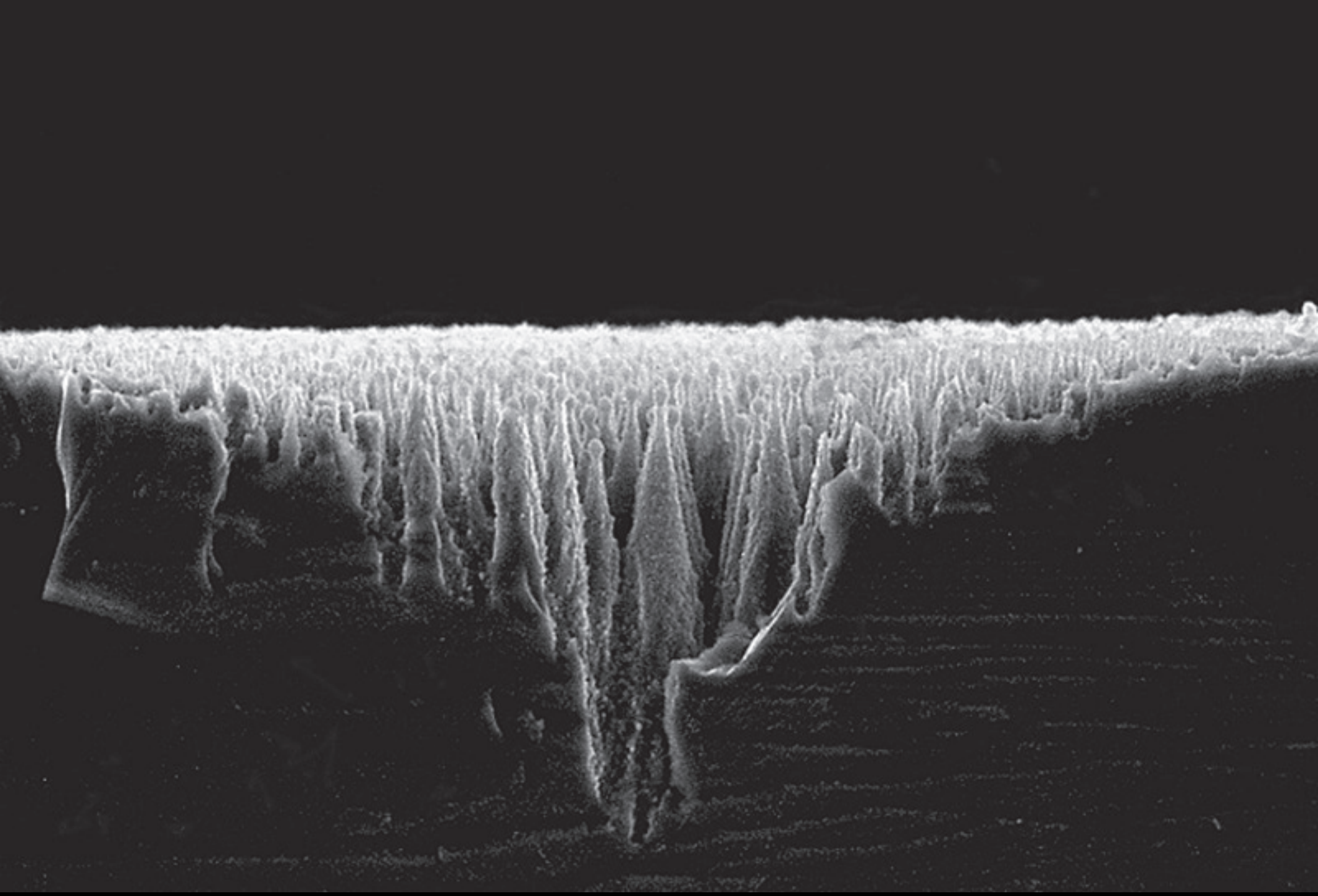

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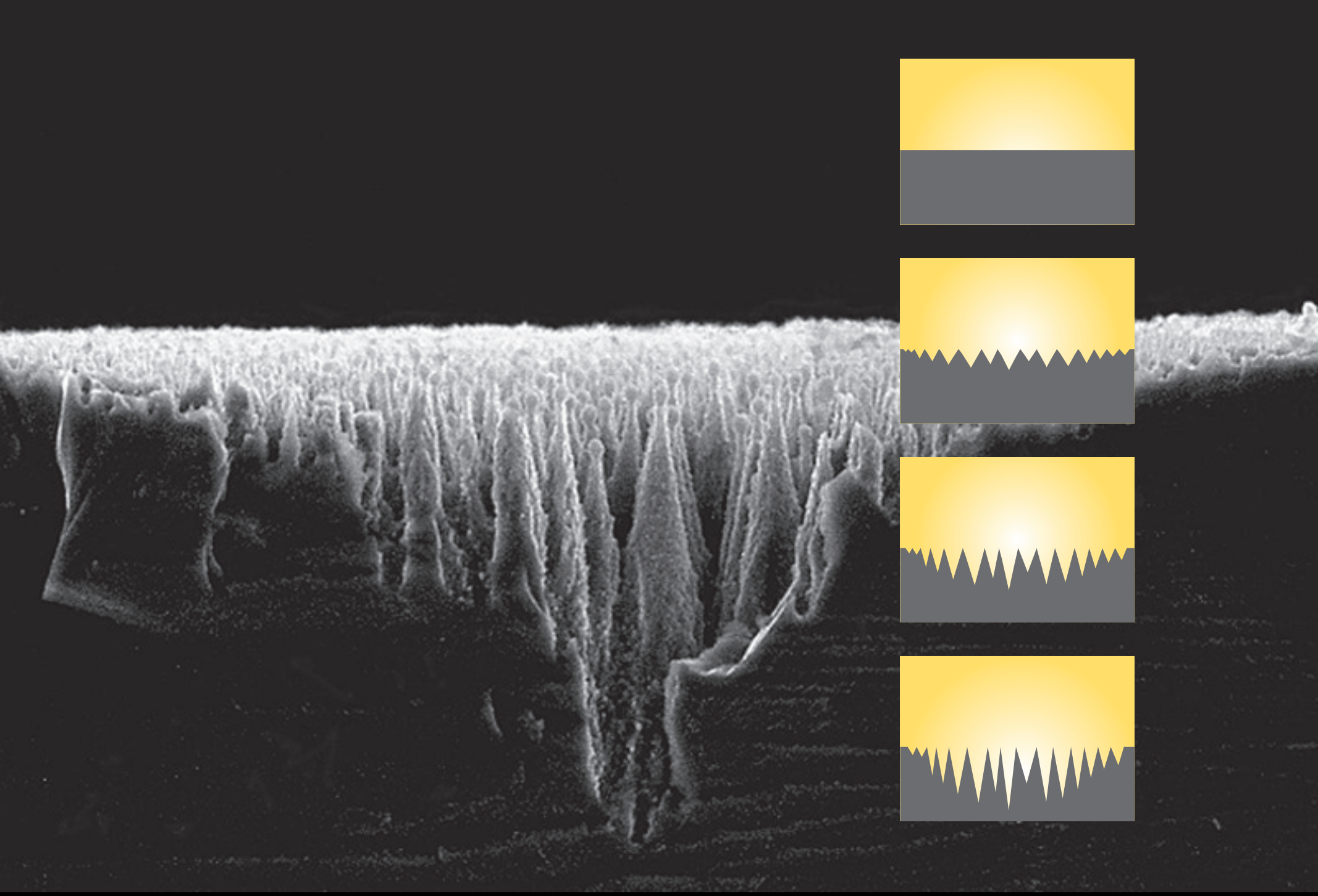

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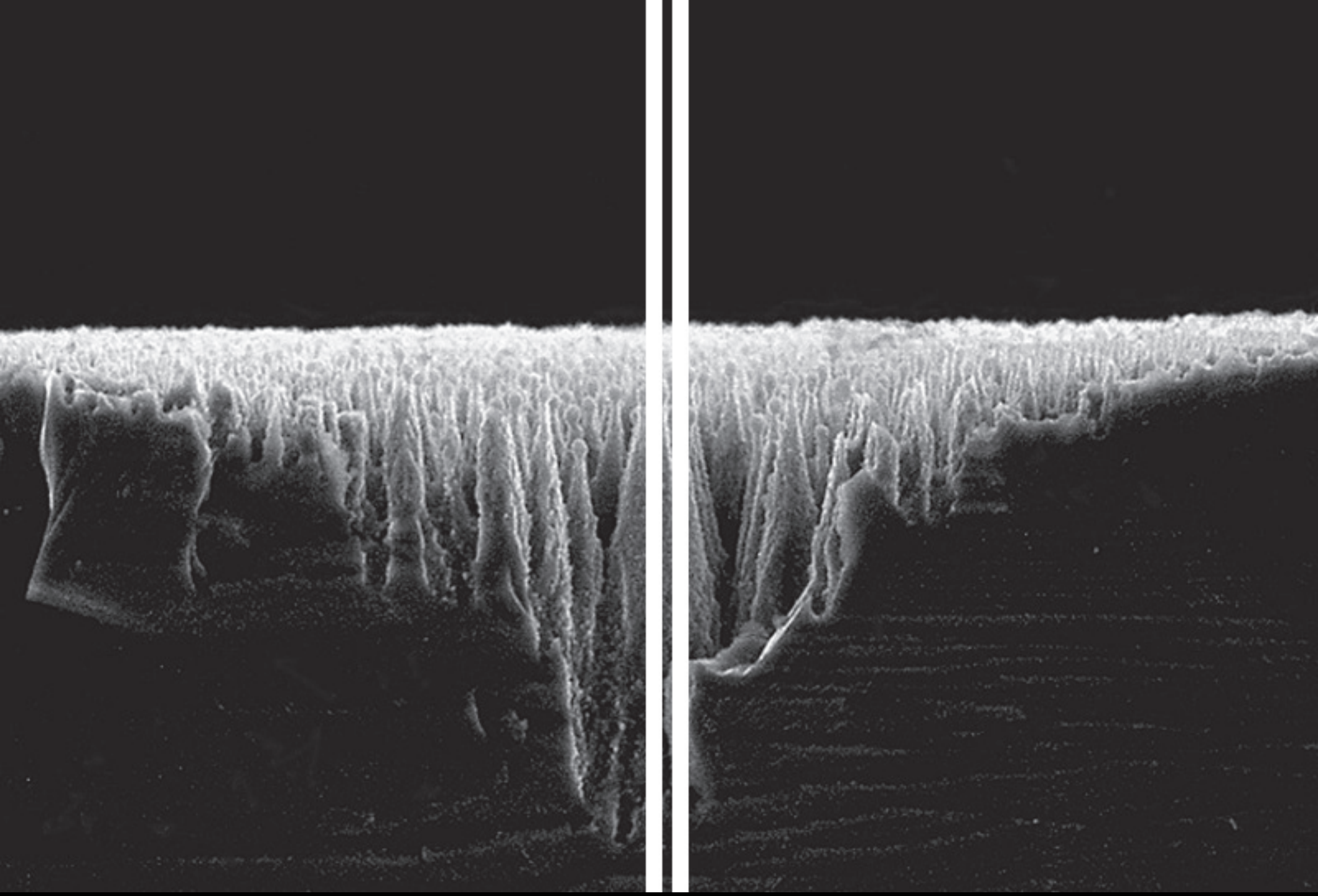

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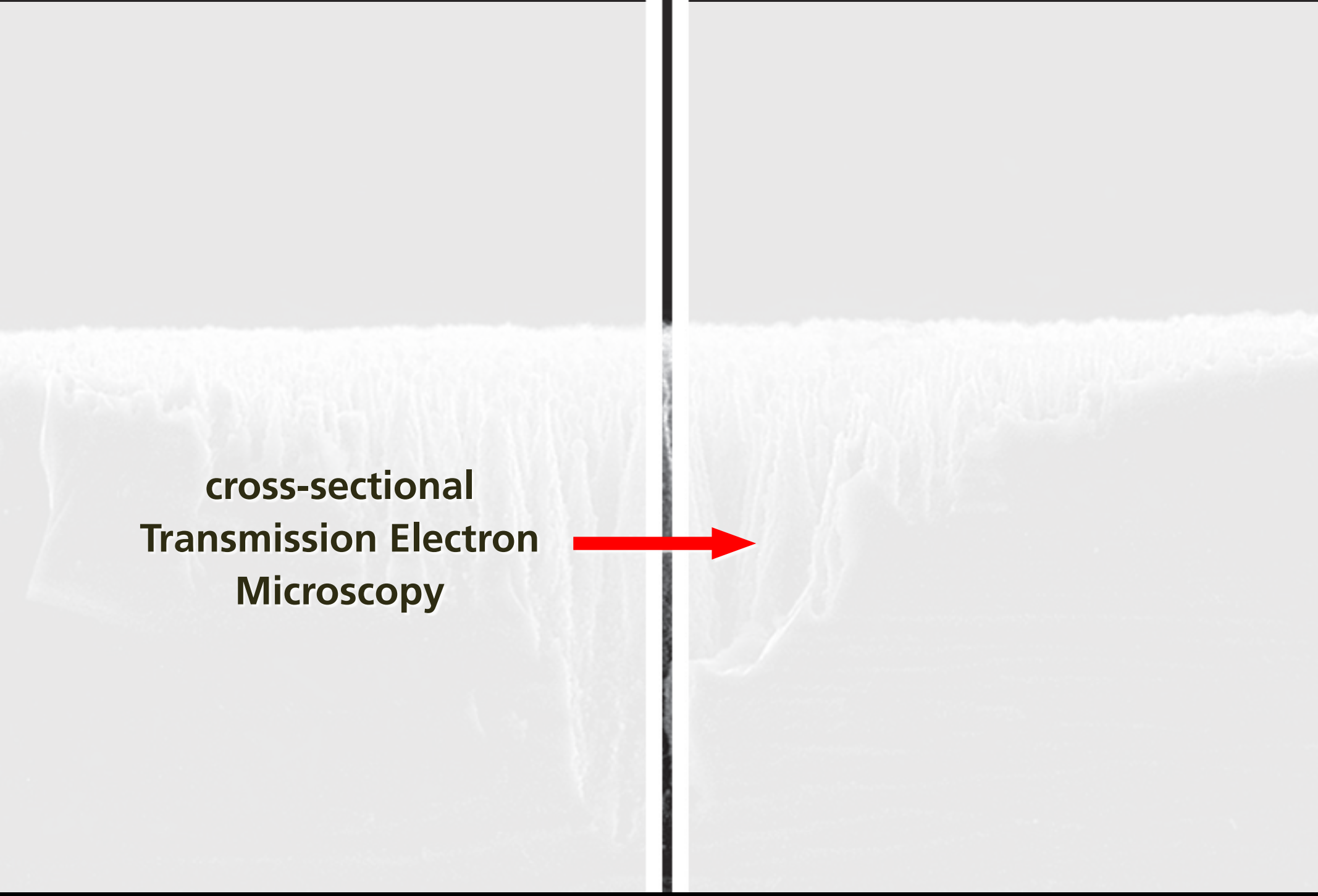

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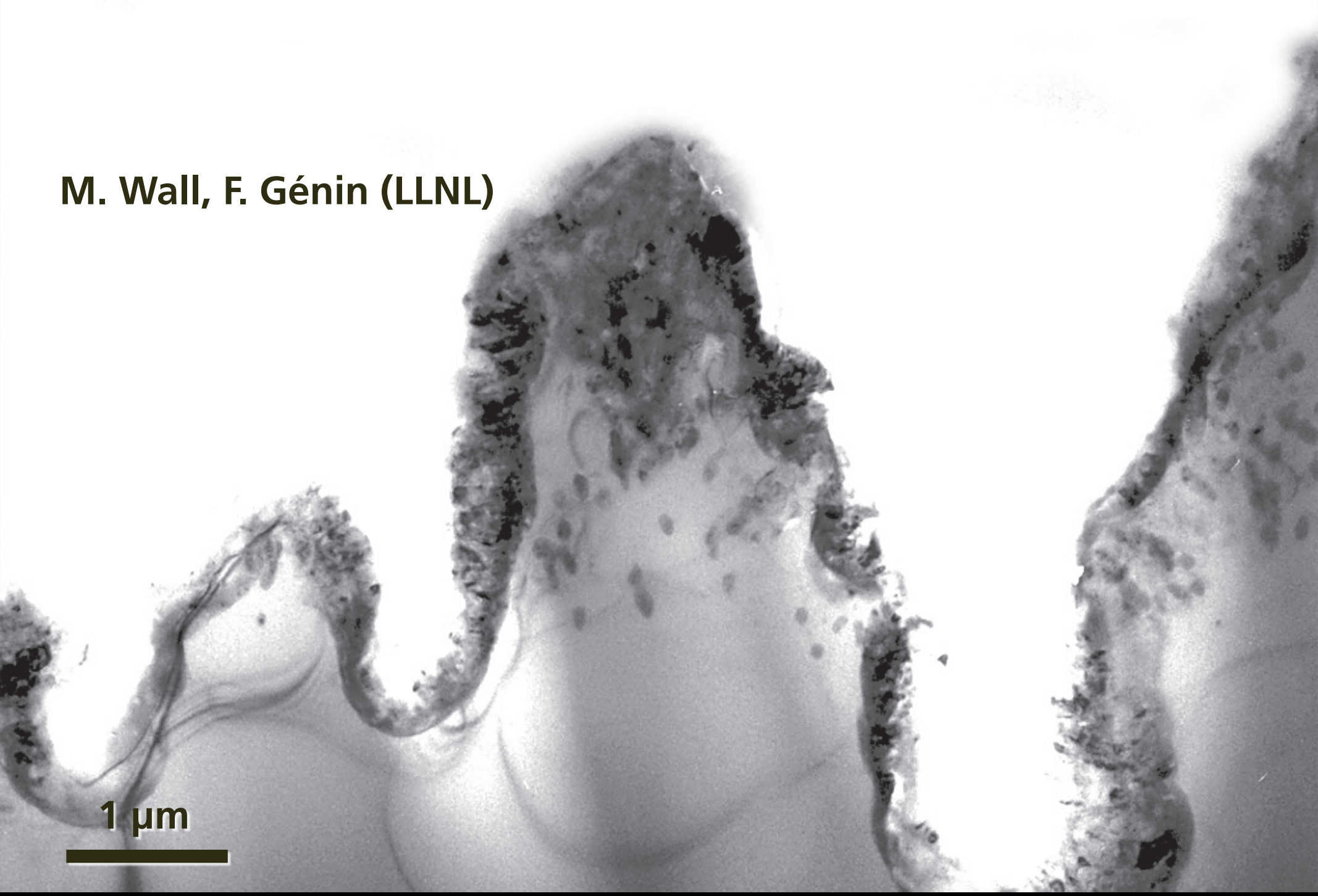
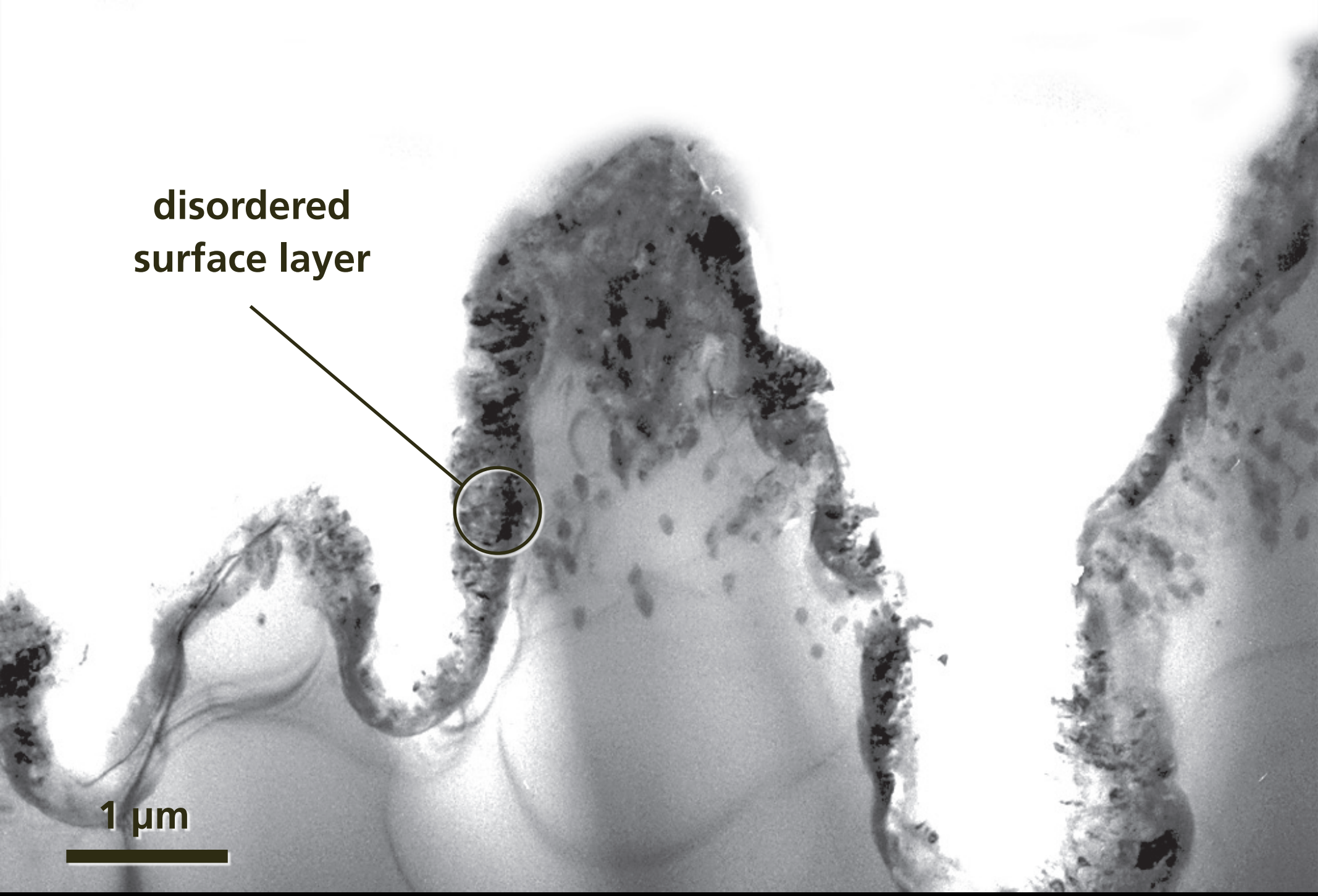


1 properties



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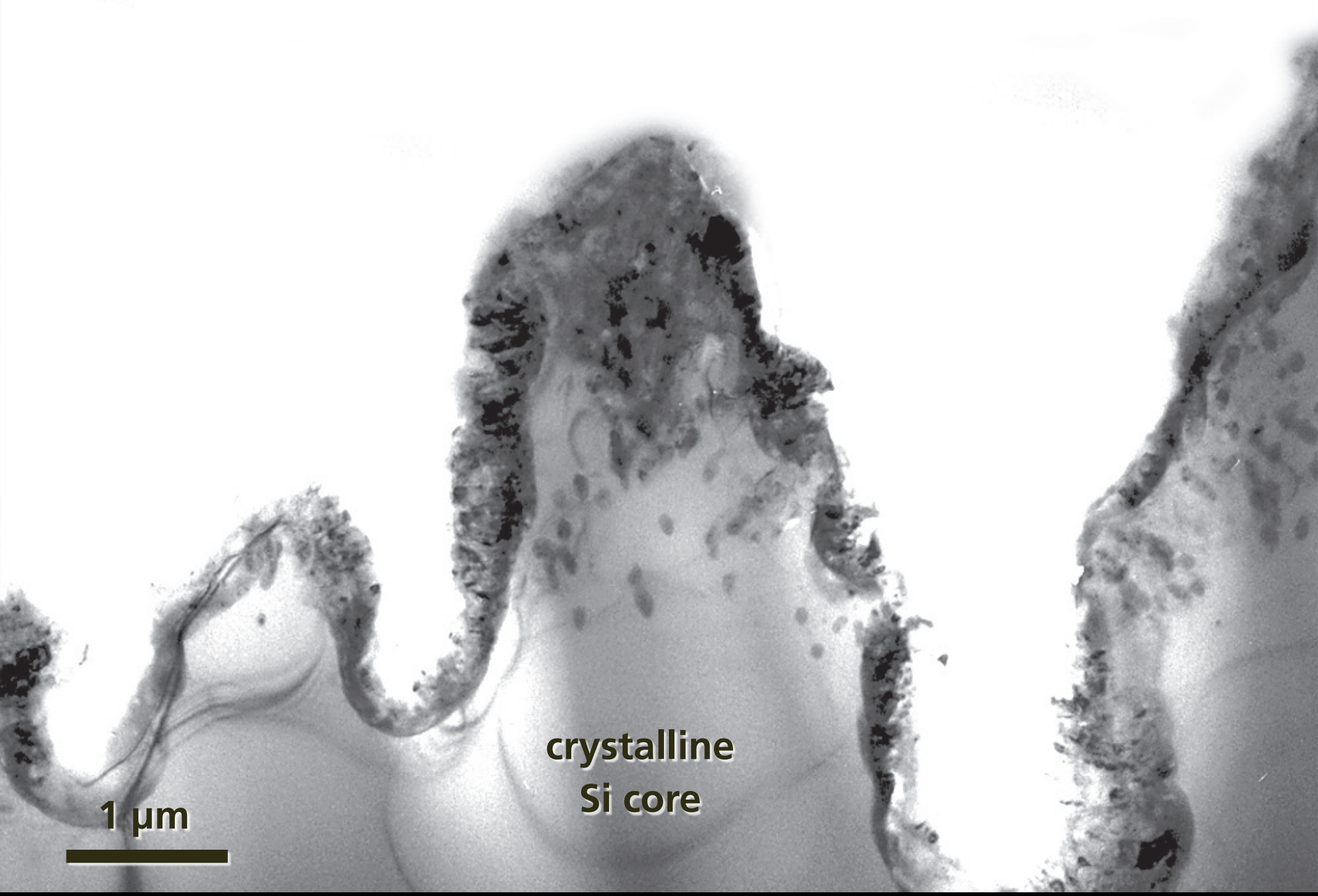
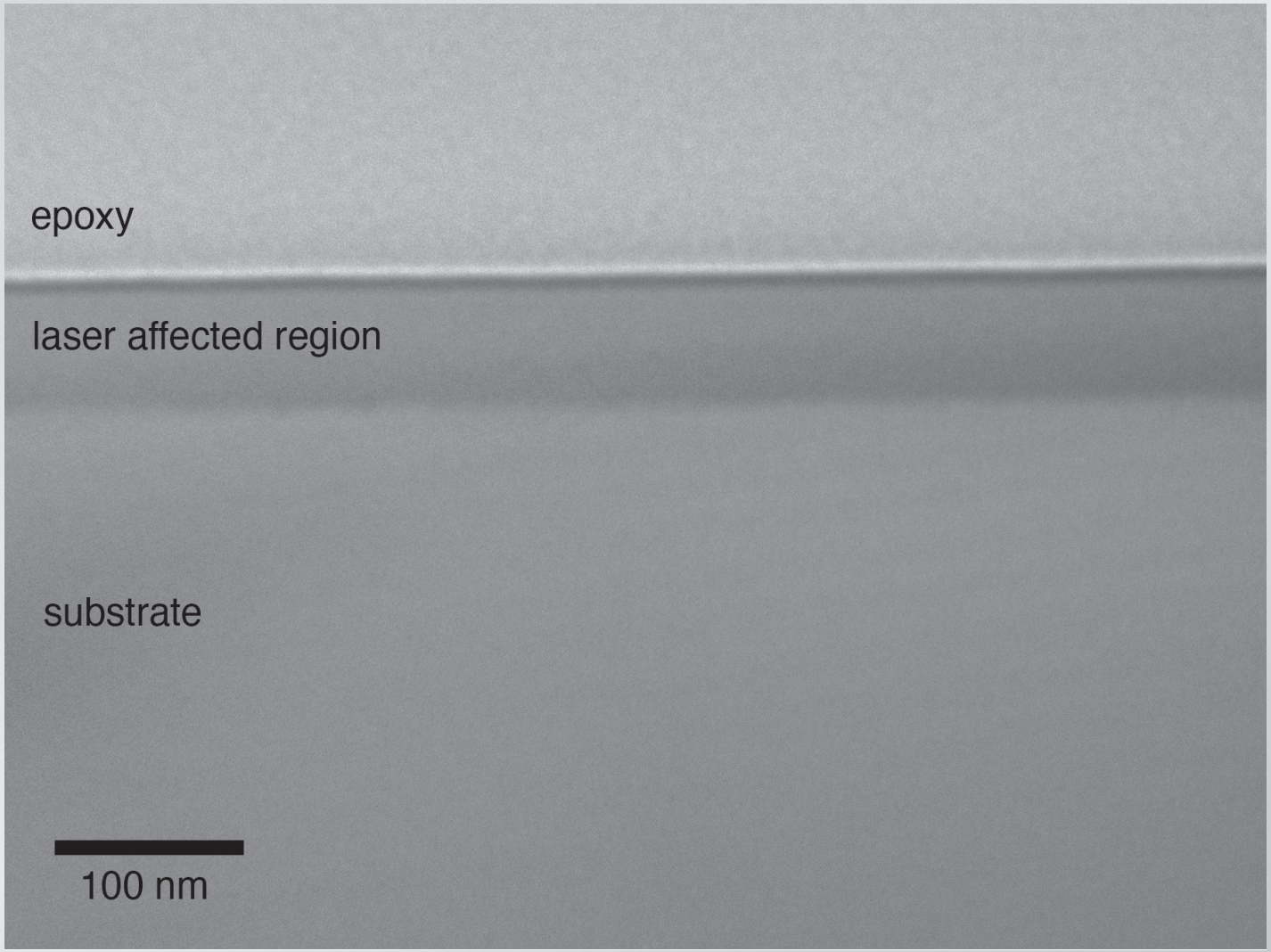
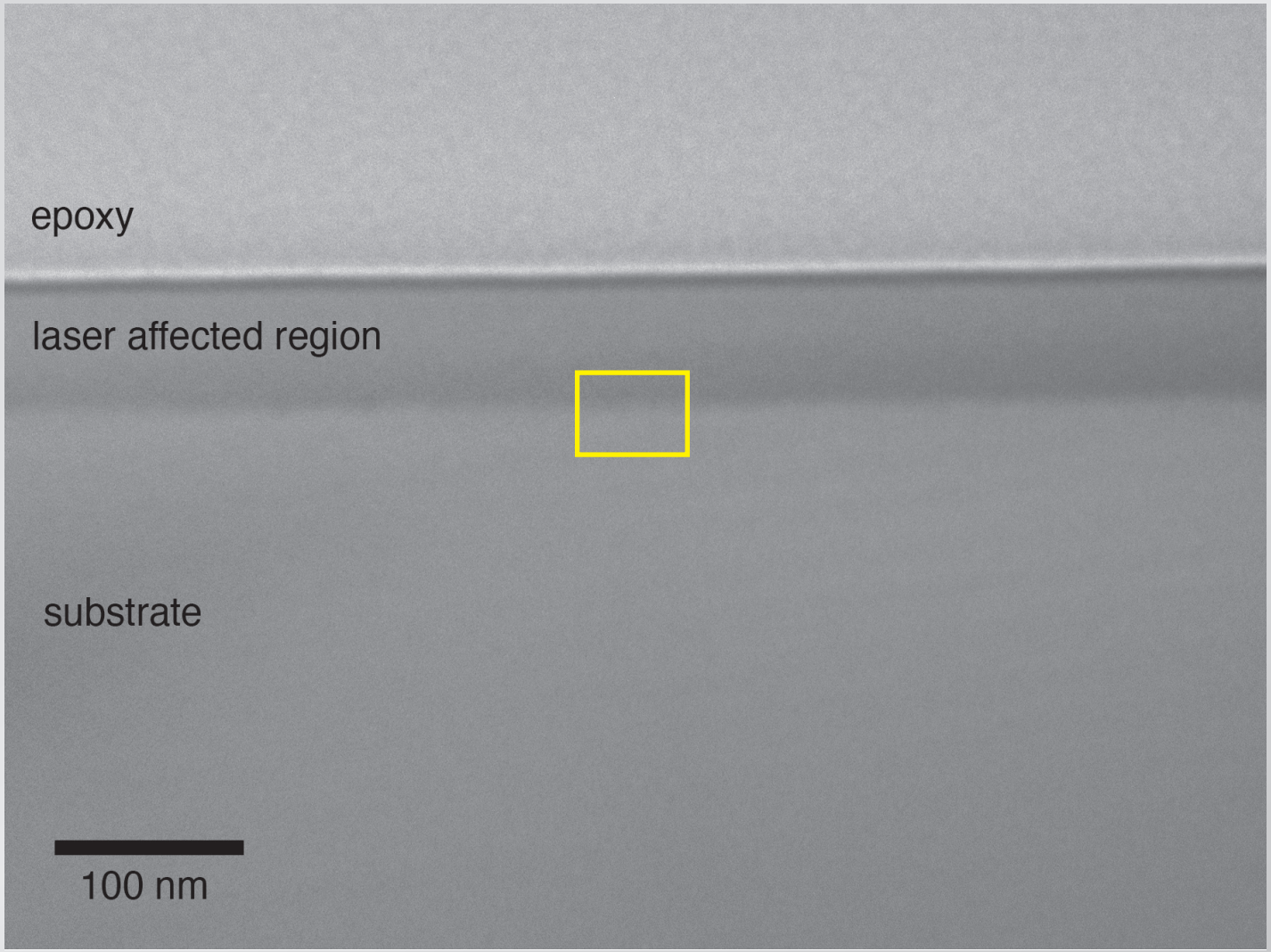


1 properties

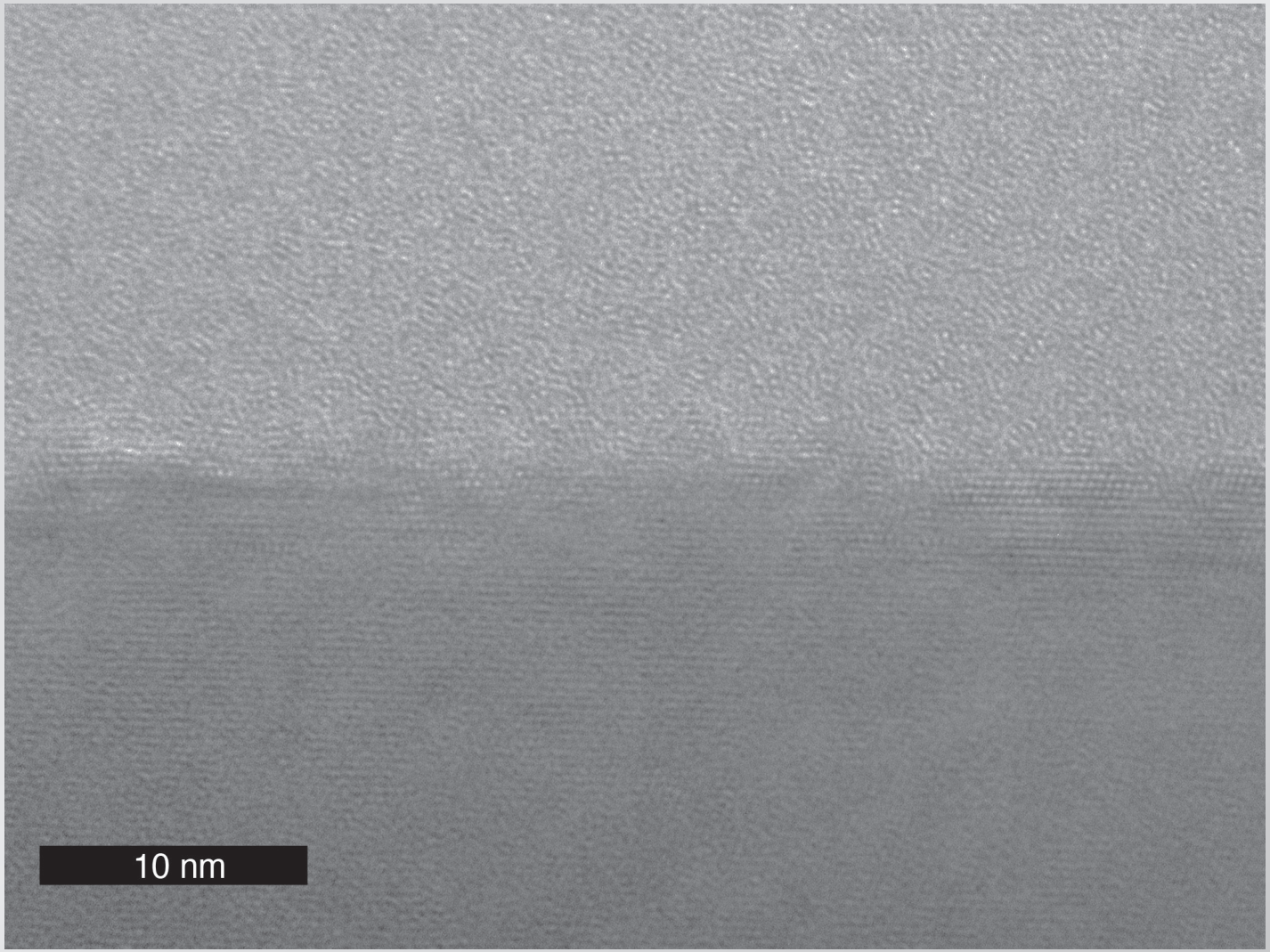
decouple ablation from melting



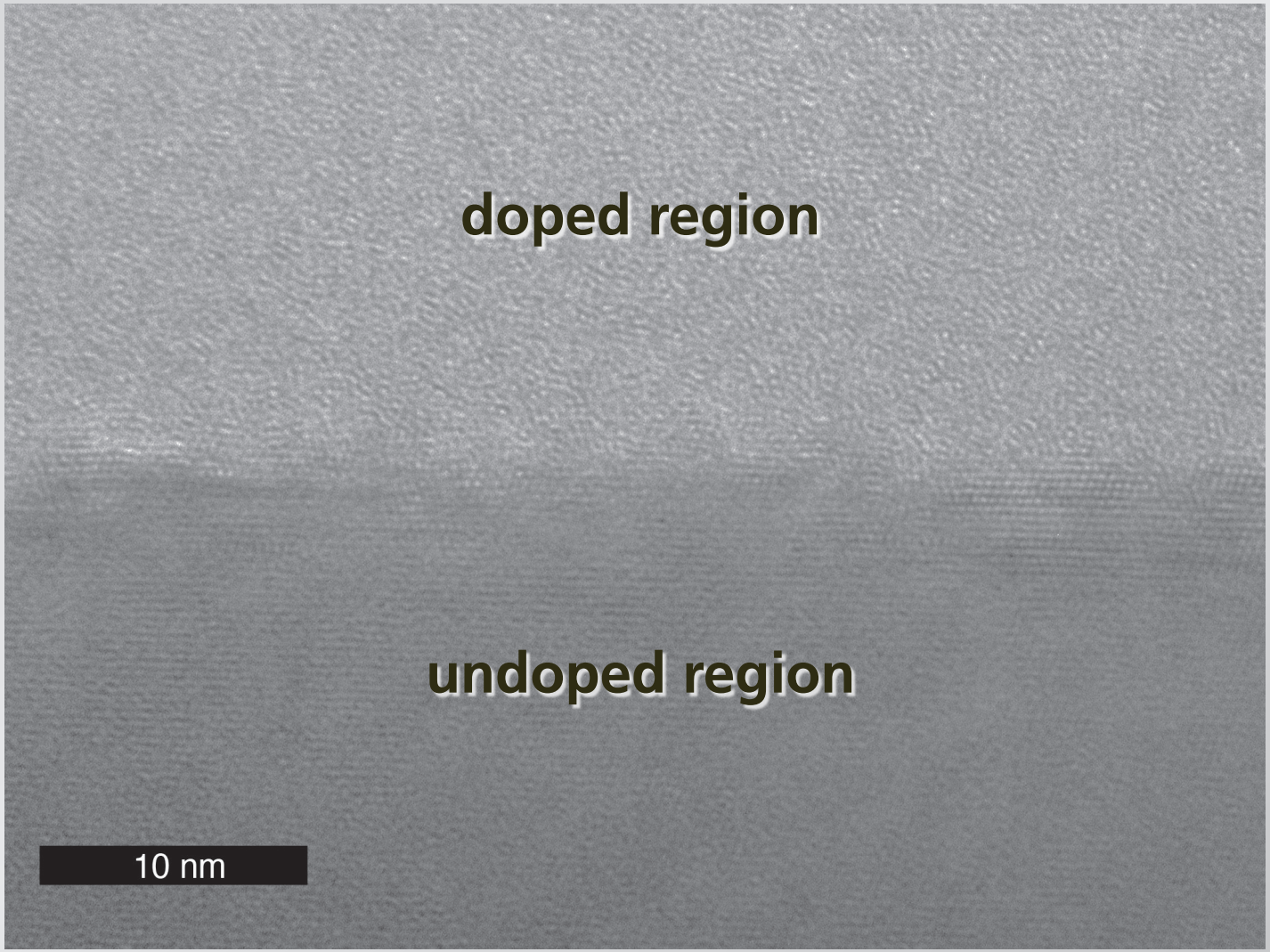
decouple ablation from melting

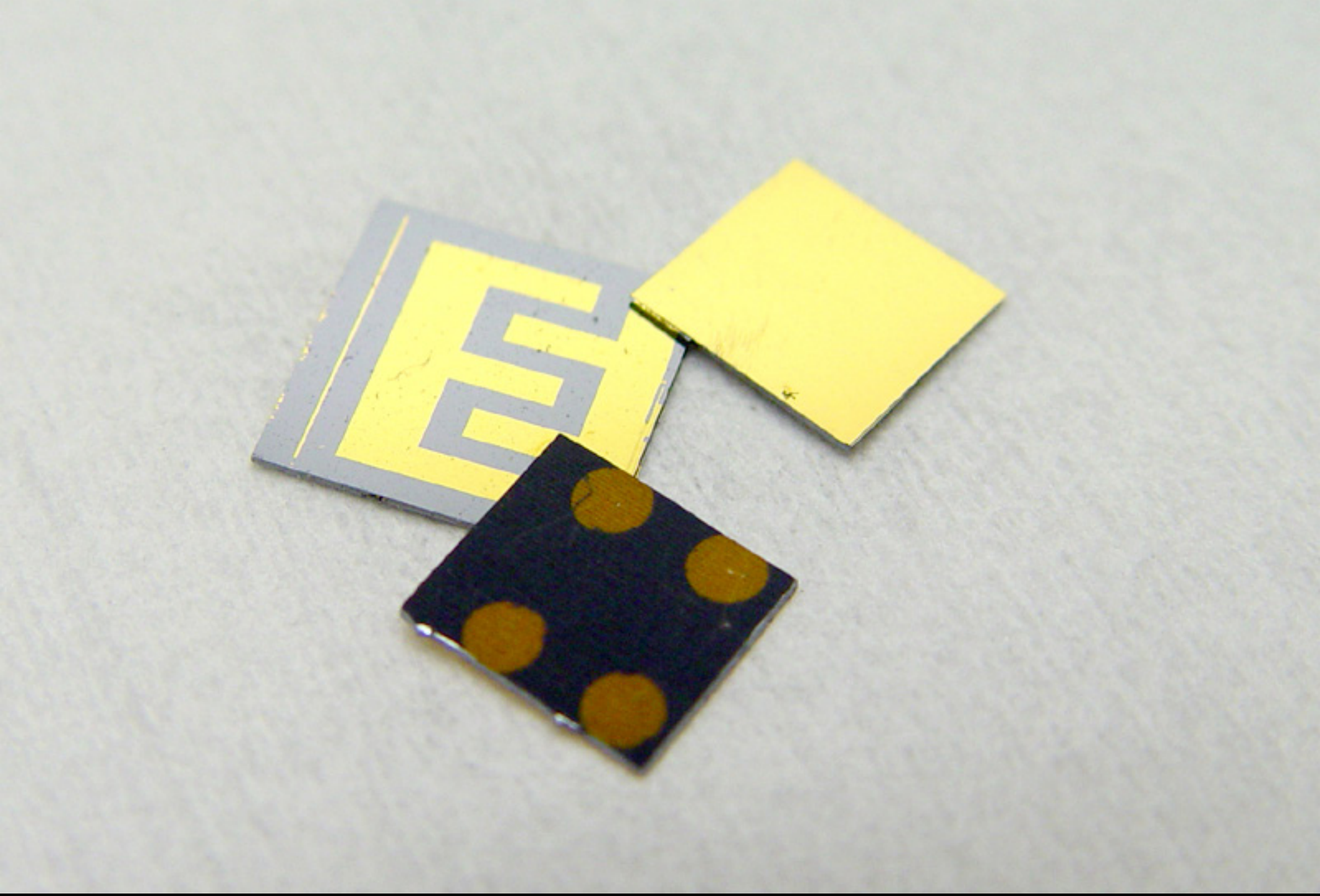


decouple ablation from melting

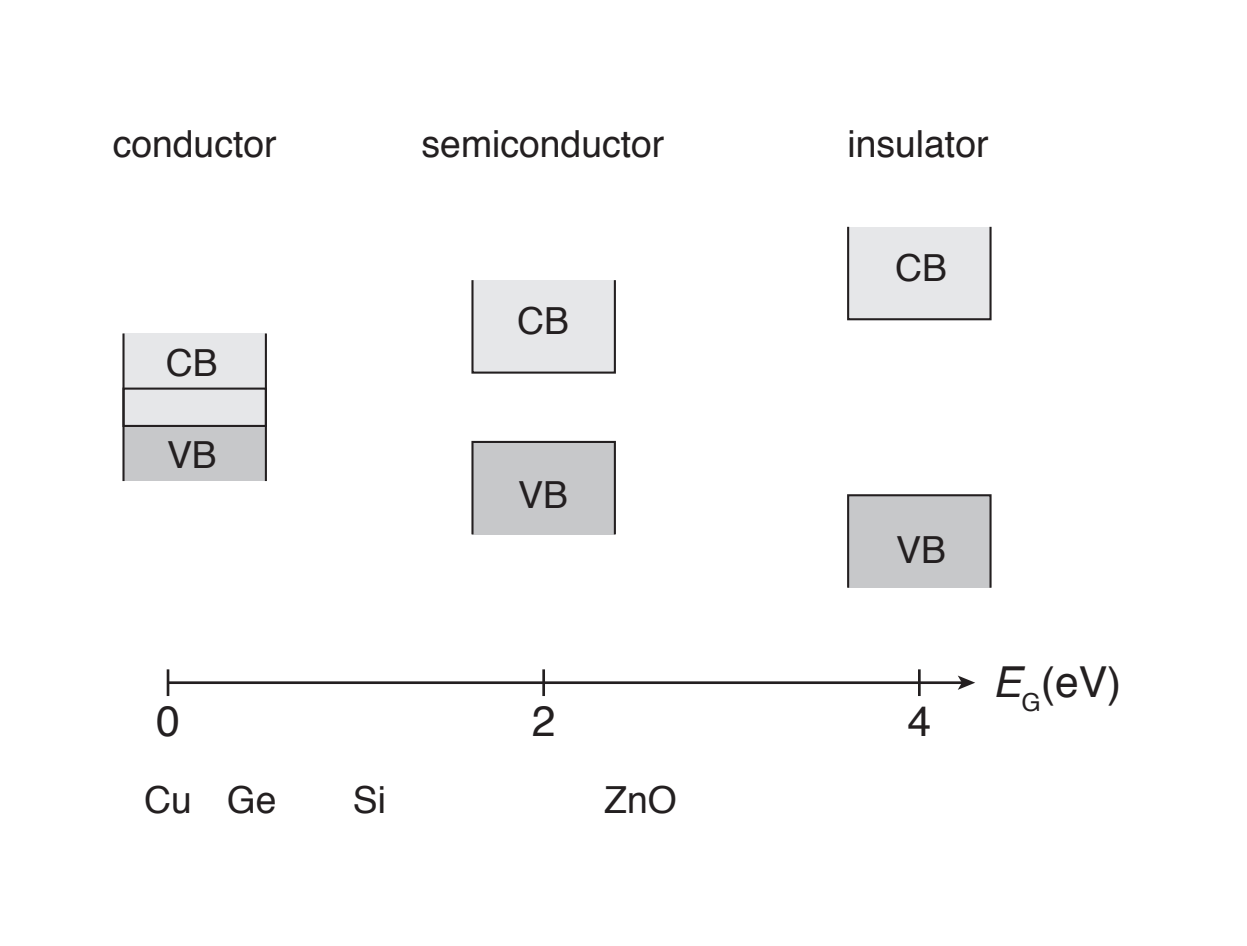


decouple ablation from melting





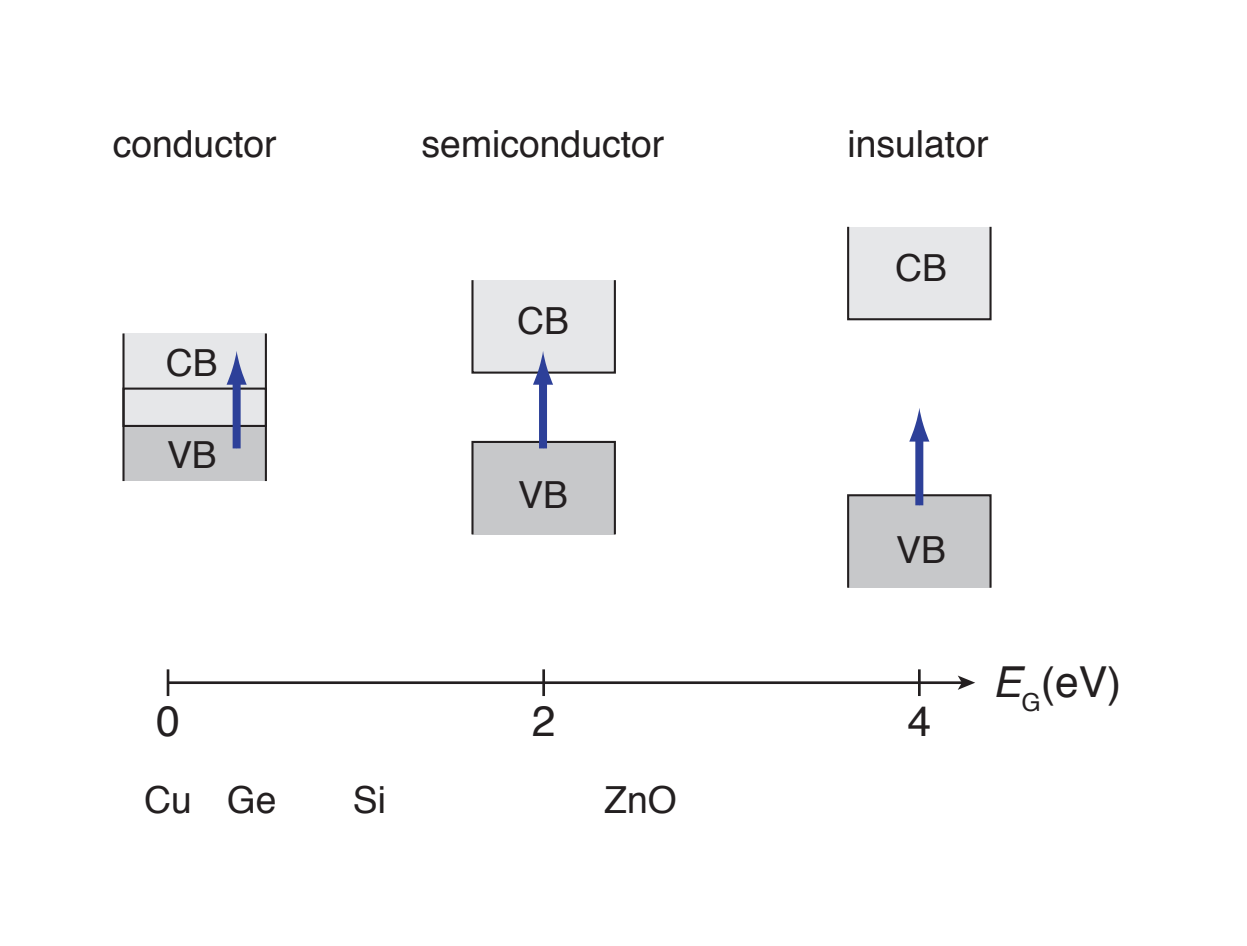
1 properties 2 intermediate band



1 properties

2 intermediate band

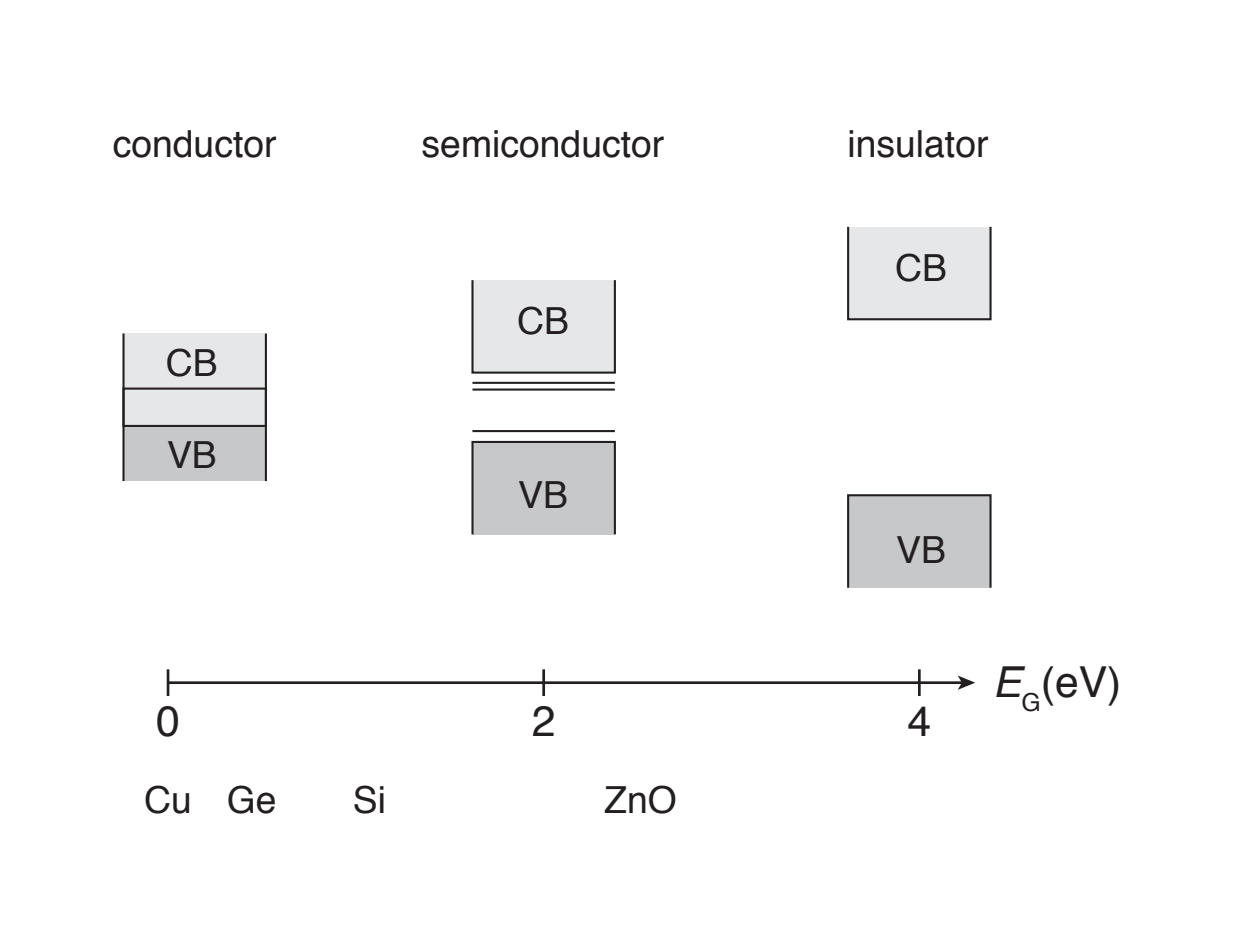
gap determines optical and electronic properties



1 properties

2 intermediate band

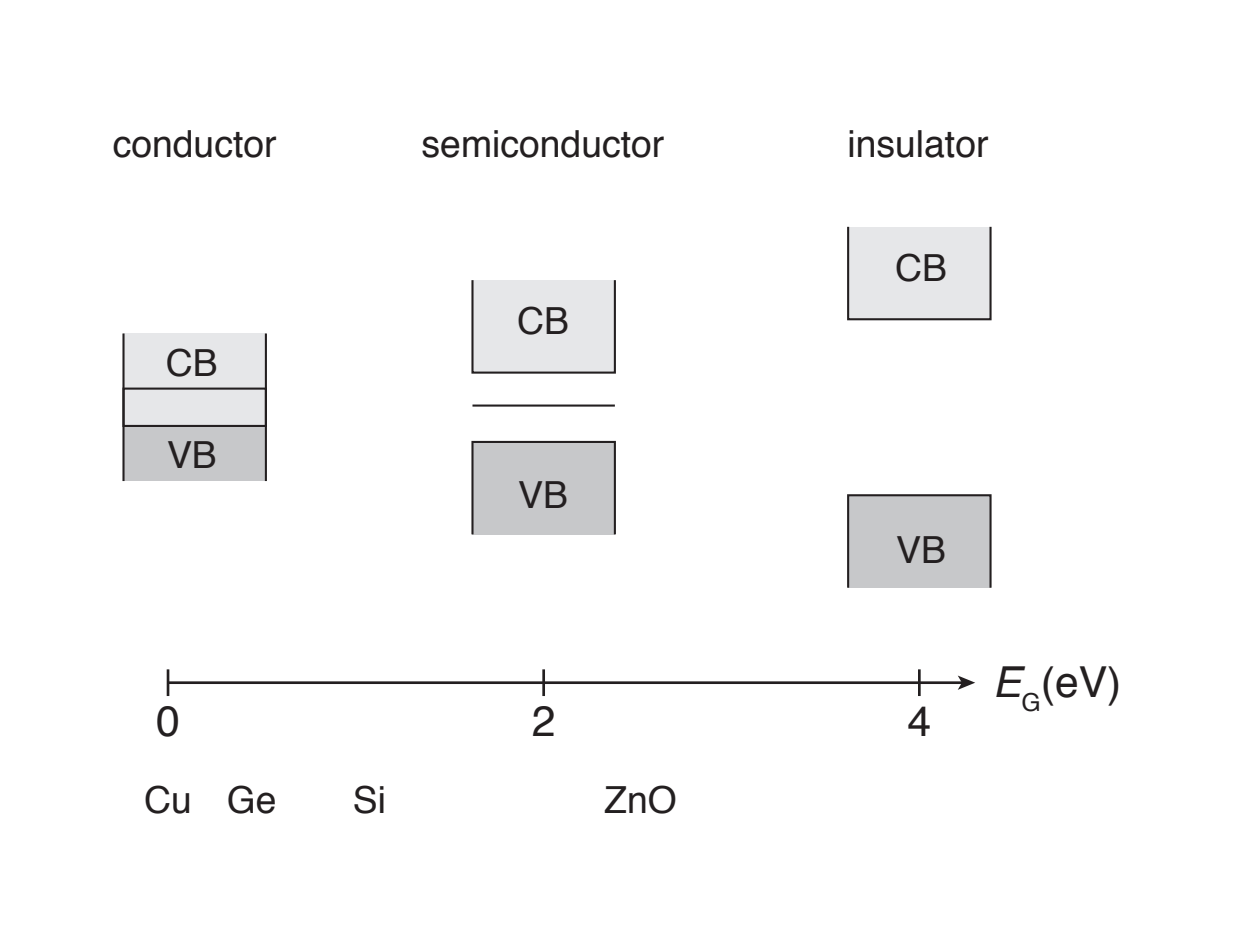
shallow-level dopants control electronic properties



1 properties

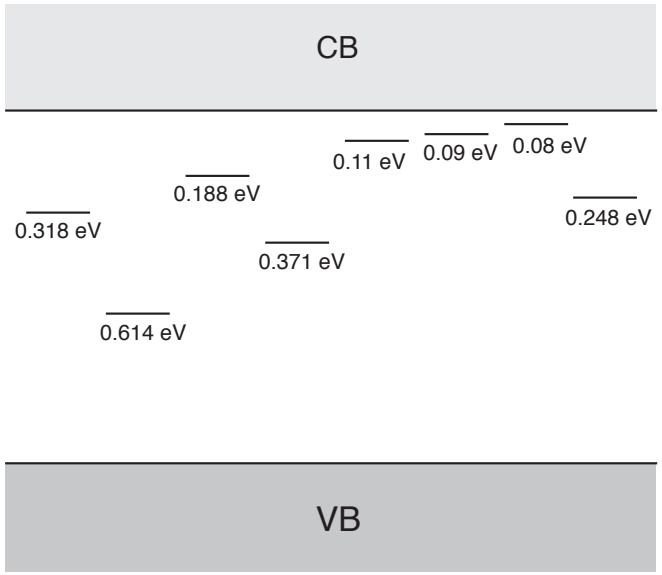
2 intermediate band

deep-level dopants typically avoided



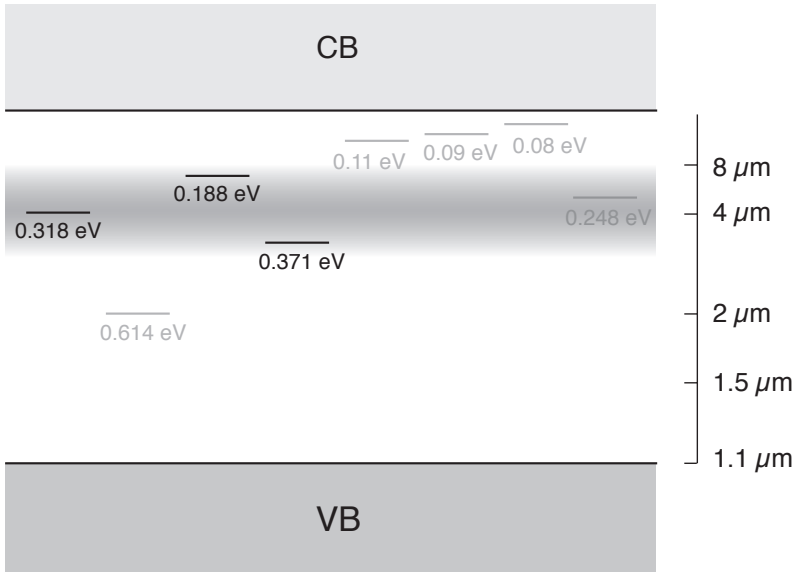
1 properties 2 intermediate band

1 part in 10^6 sulfur introduces donor states in gap



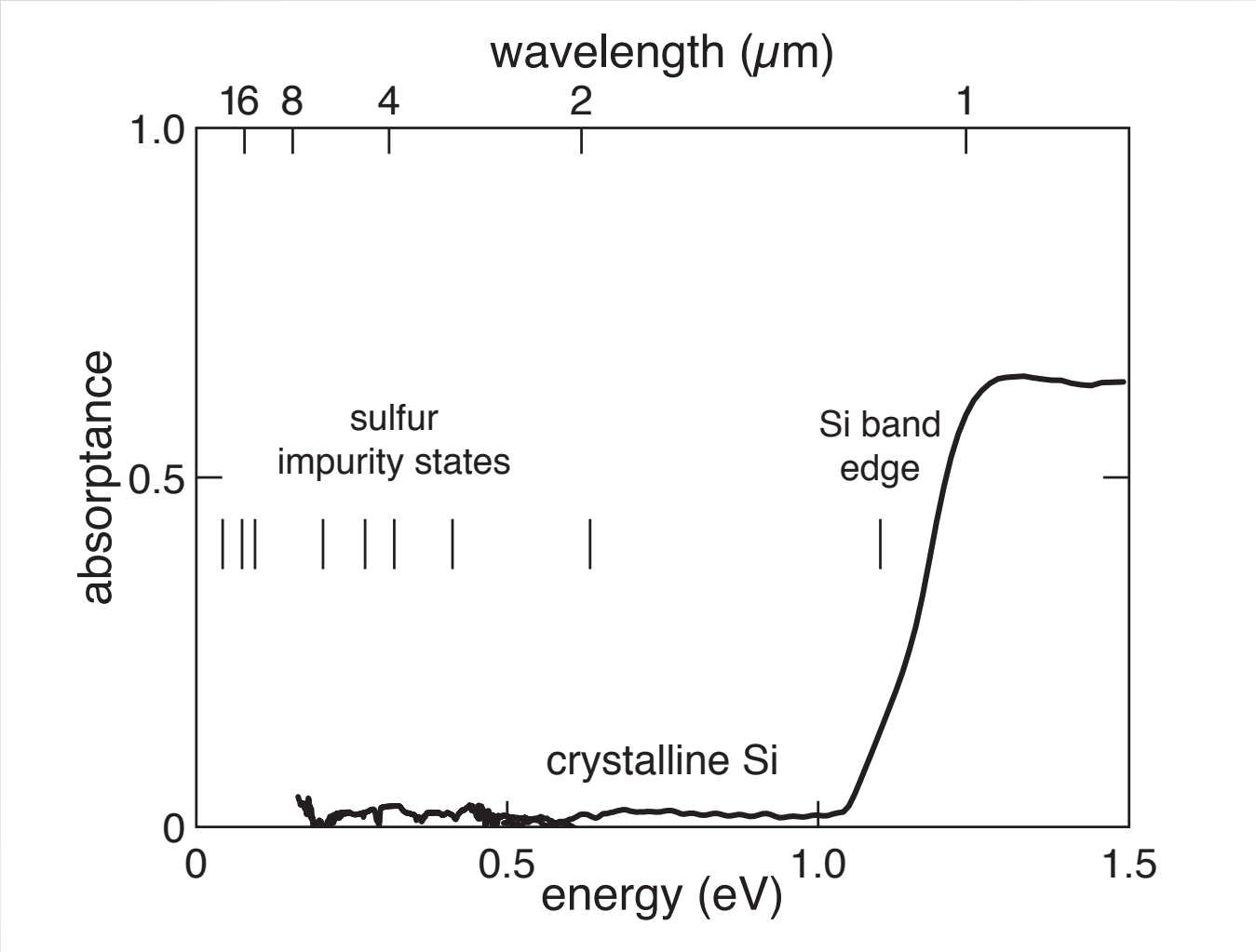
Janzén *et al.*, Phys. Rev. B 29, 1907 (1984)

at high concentration states broaden into band



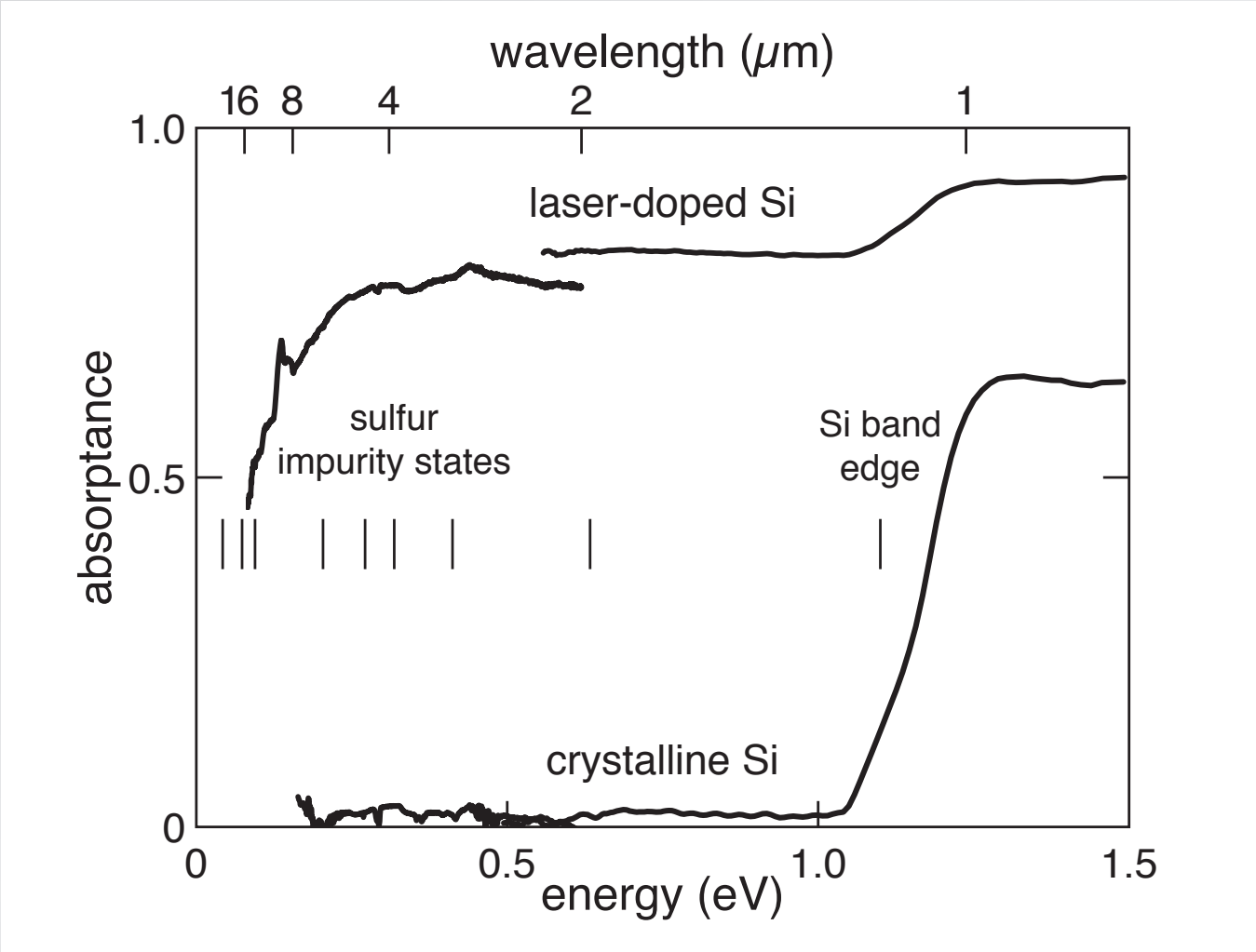
1 properties 2 intermediate band

10^{-6} sulfur doping



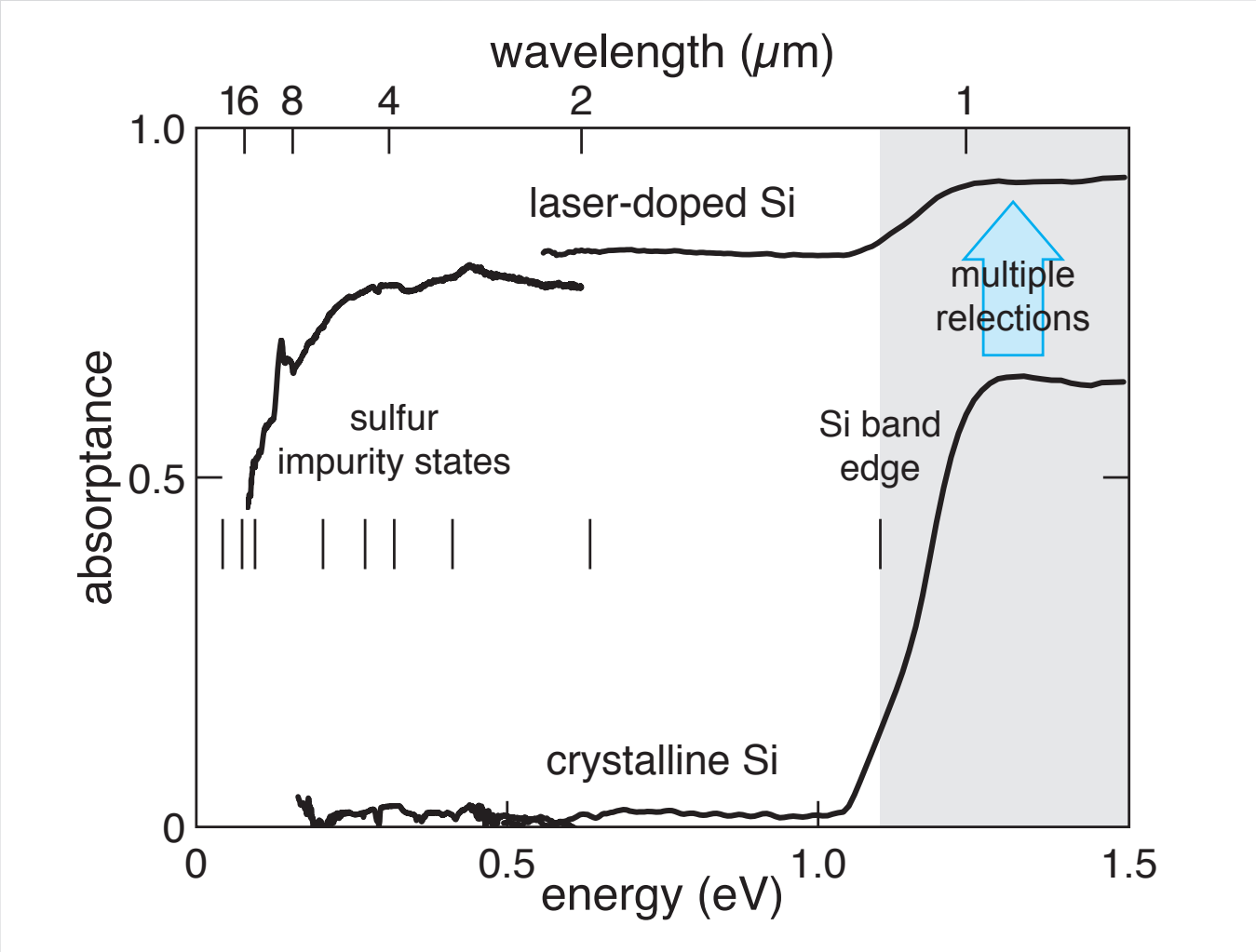
1 properties 2 intermediate band

laser-doped S:Si



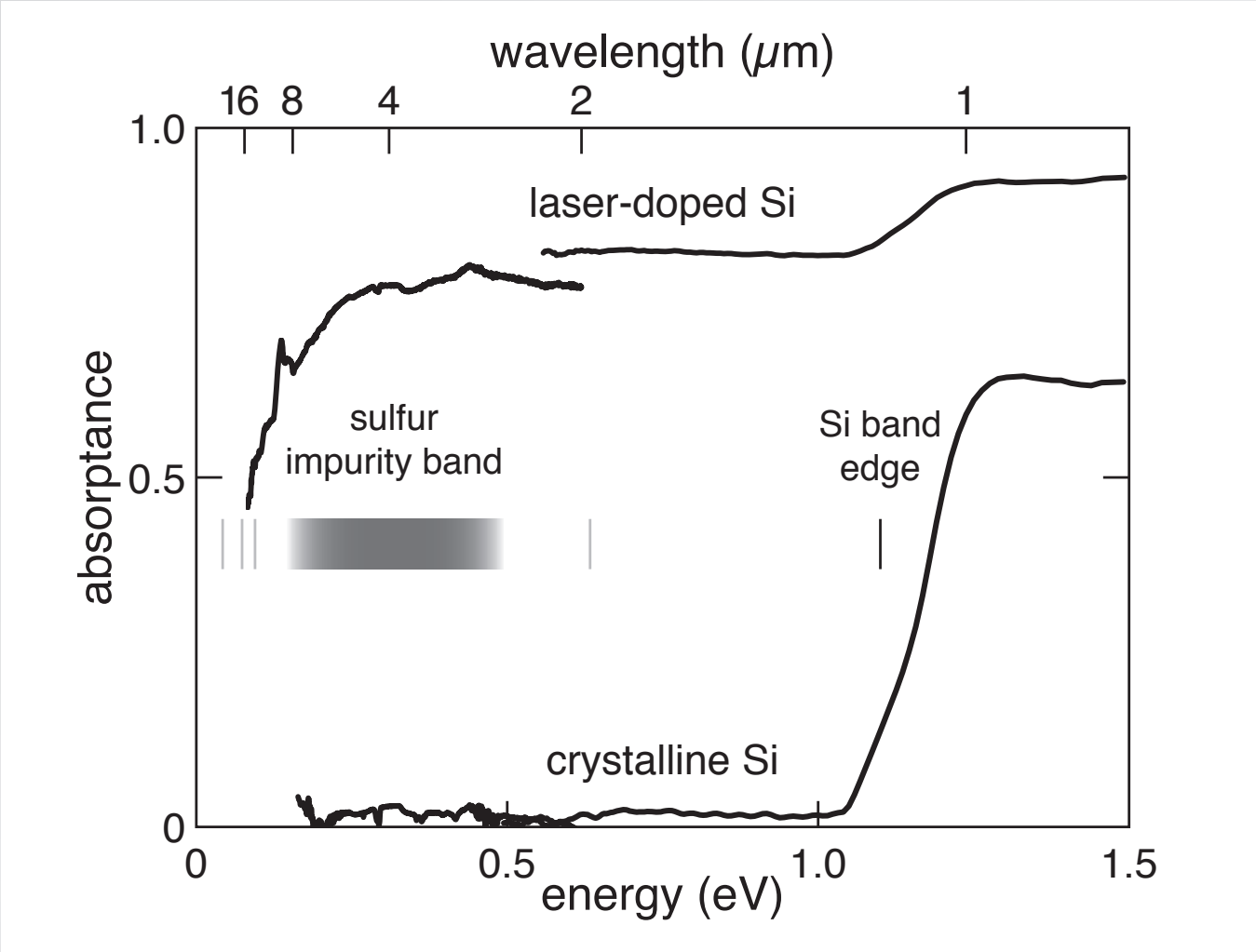
1 properties 2 intermediate band

laser-doped S:Si

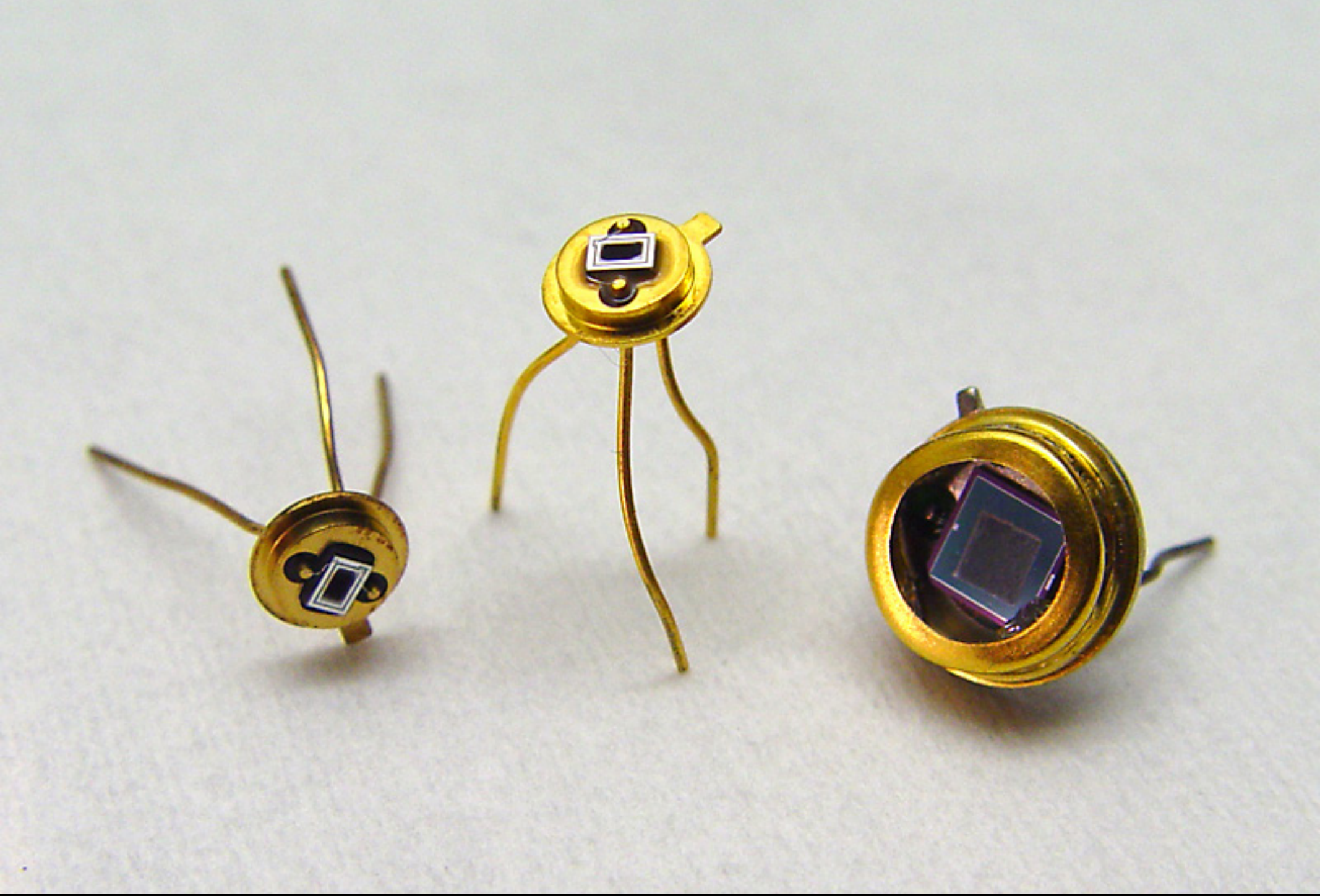


1 properties 2 intermediate band

laser-doped S:Si

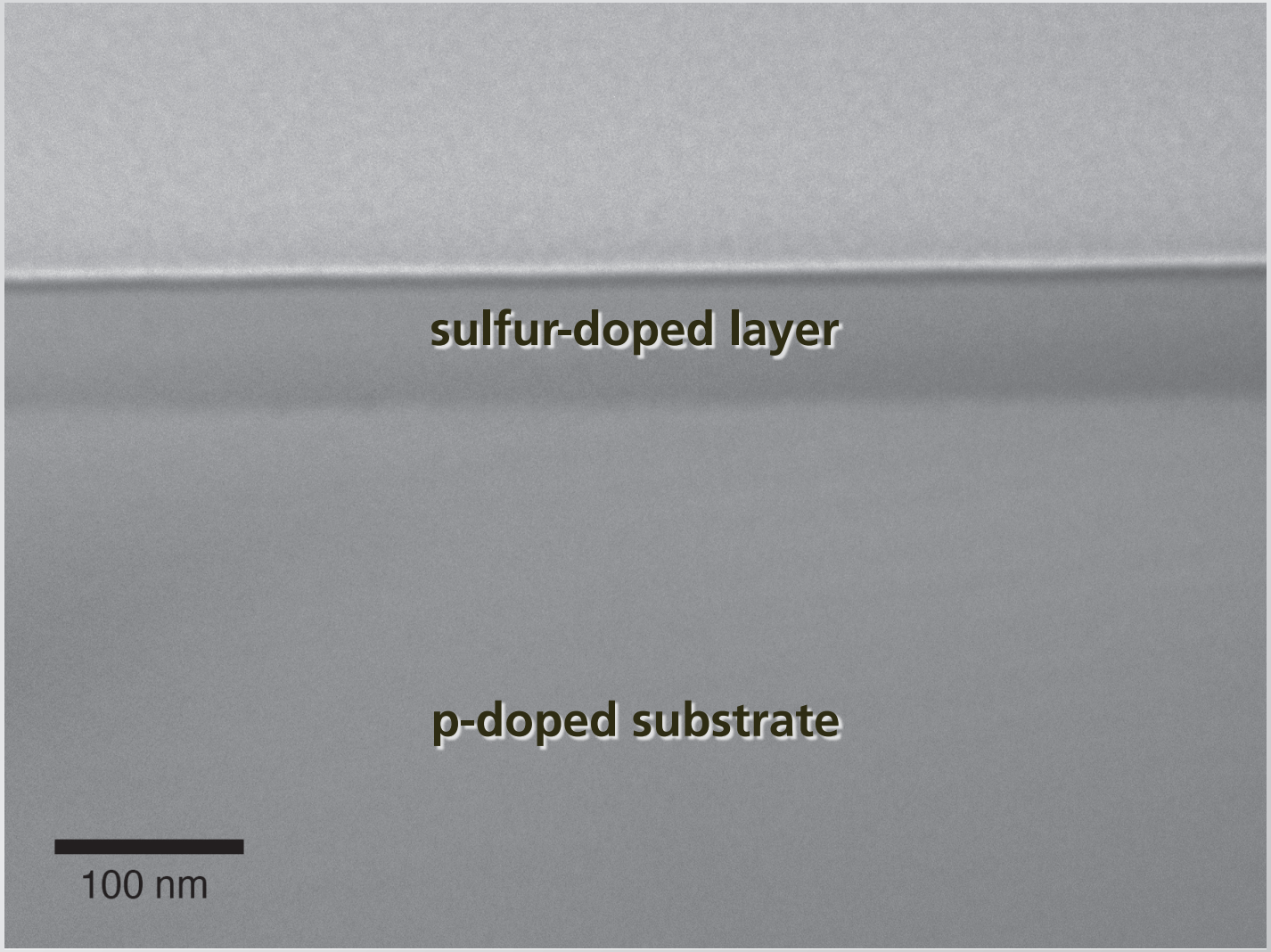


1 properties 2 intermediate band

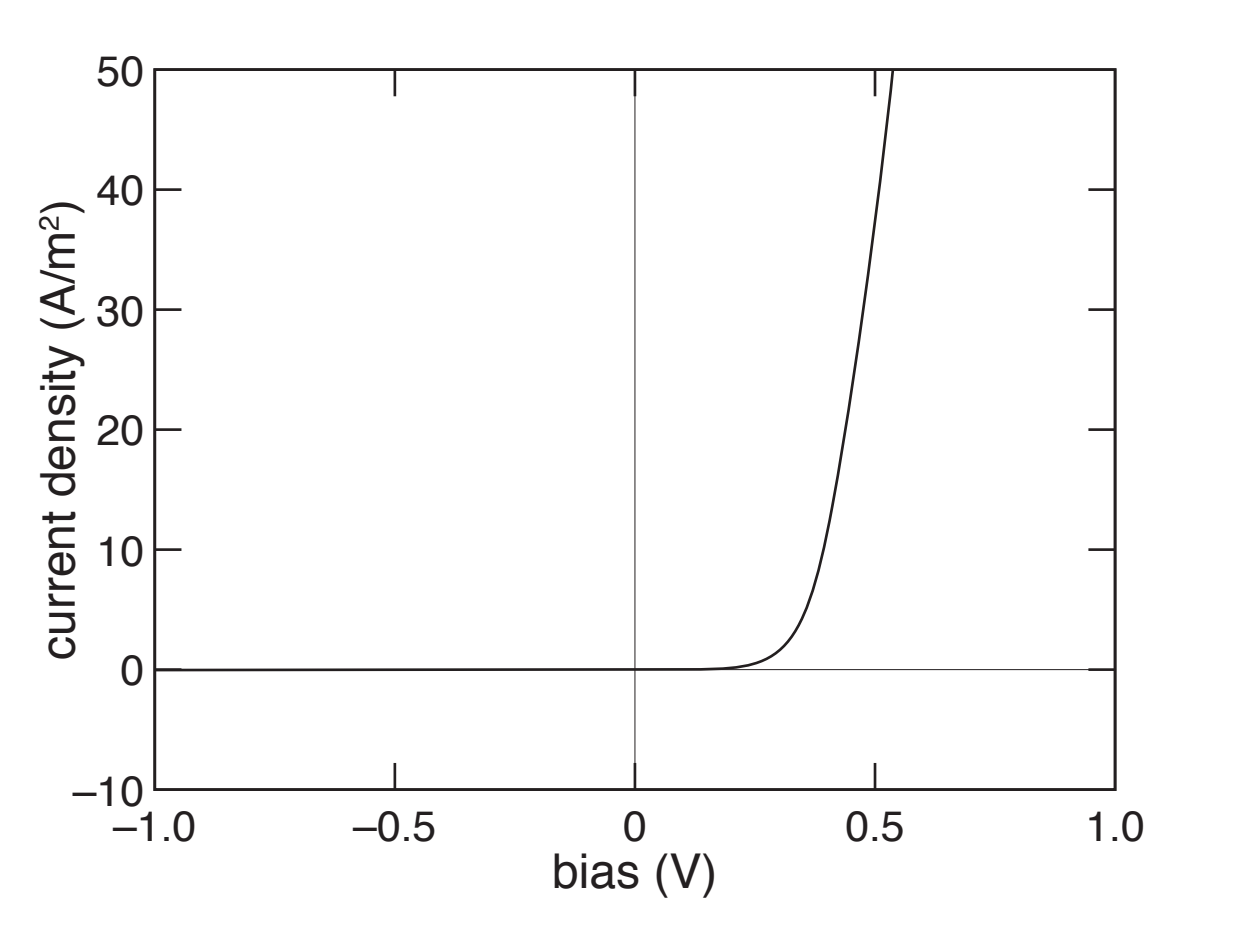


1 properties 2 intermediate band 3 devices

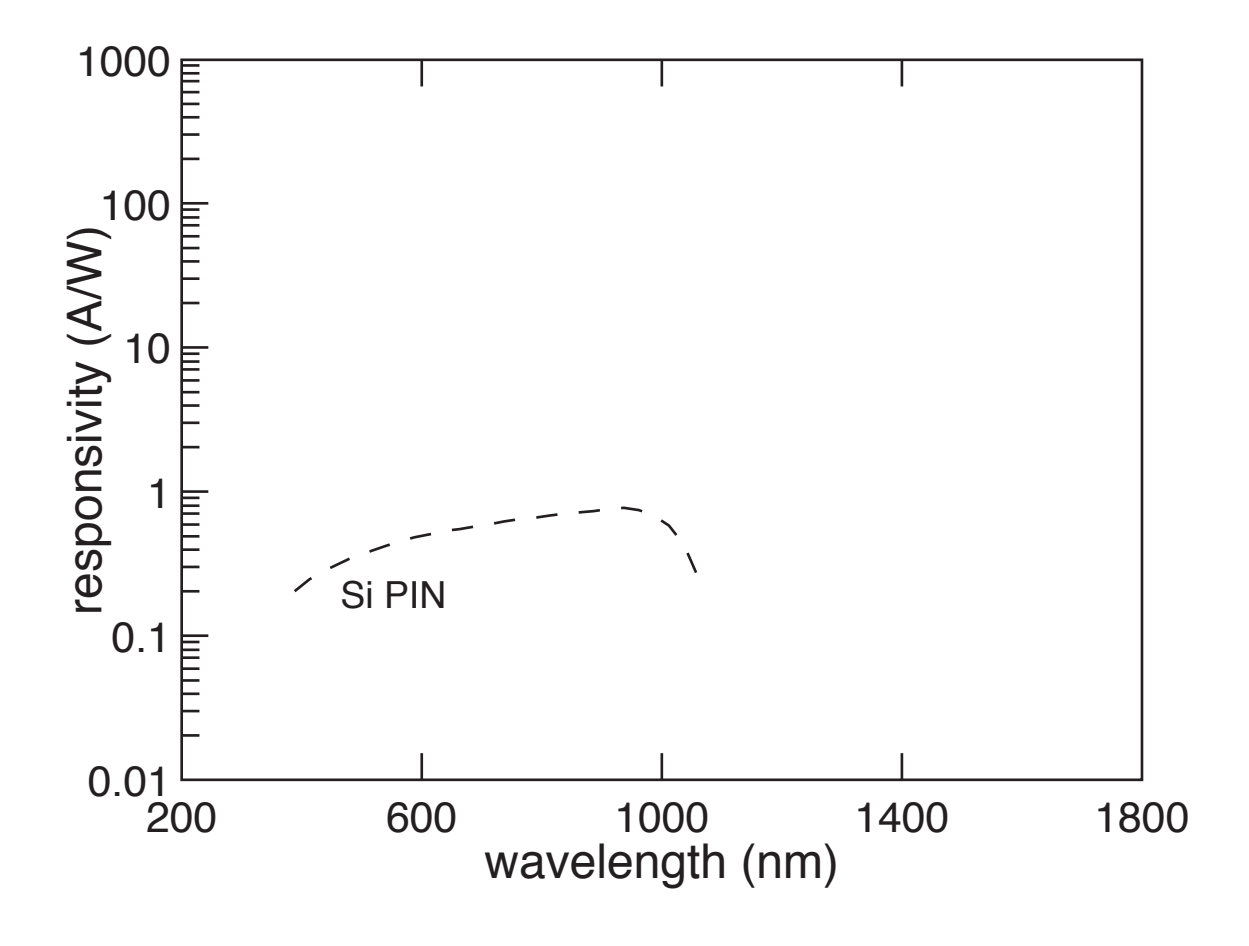
should have shallow junction below surface



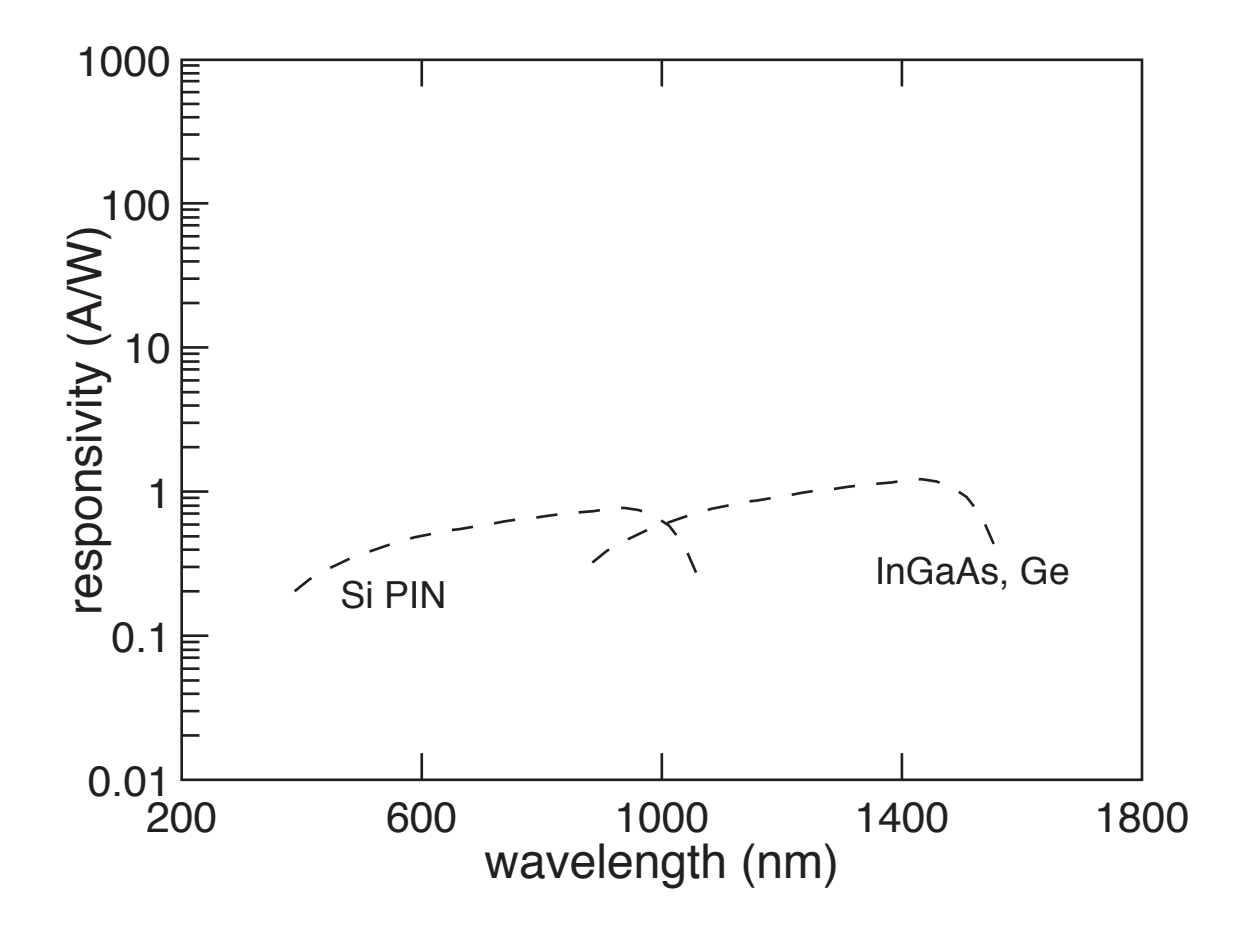
excellent rectification (after annealing)



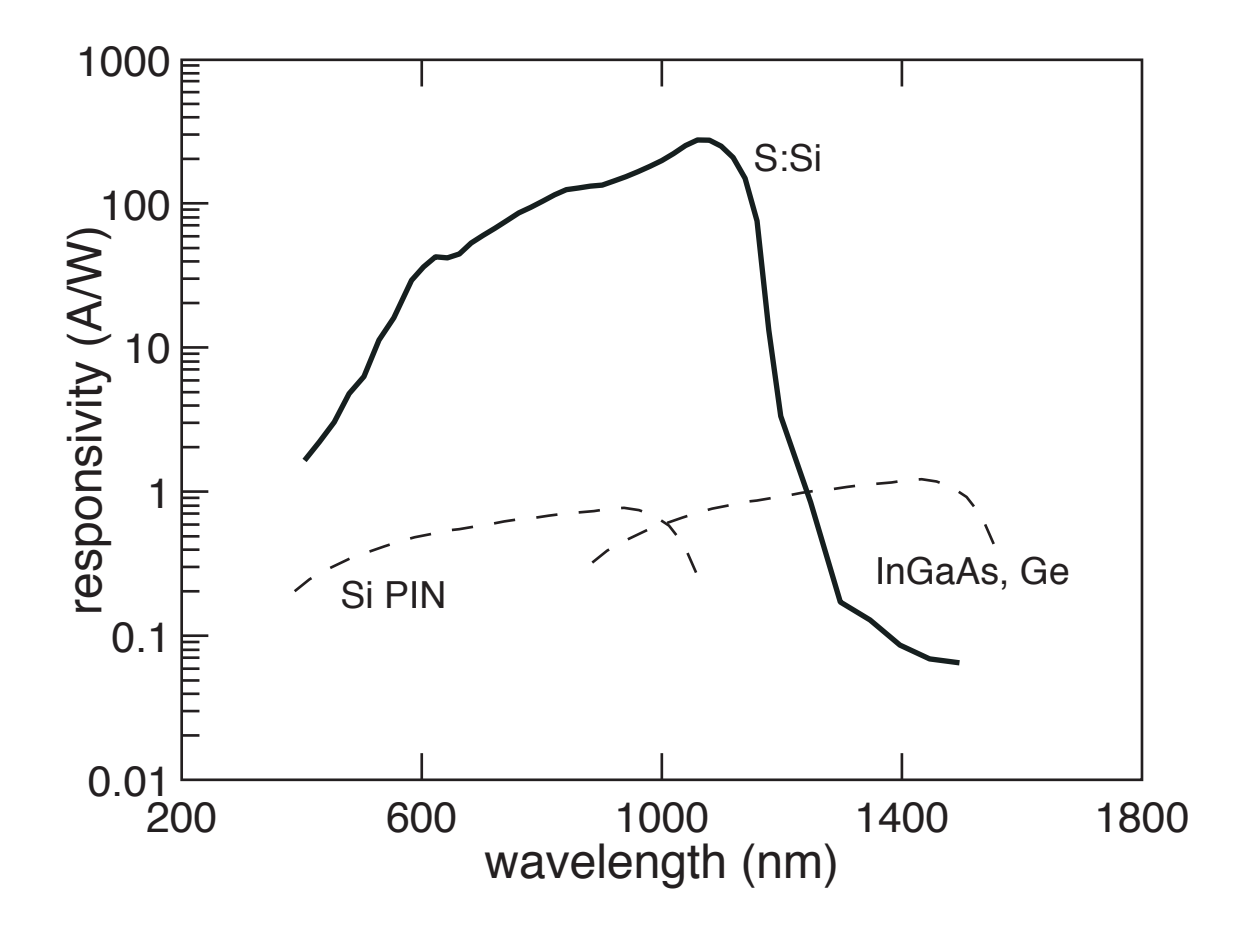
responsivity



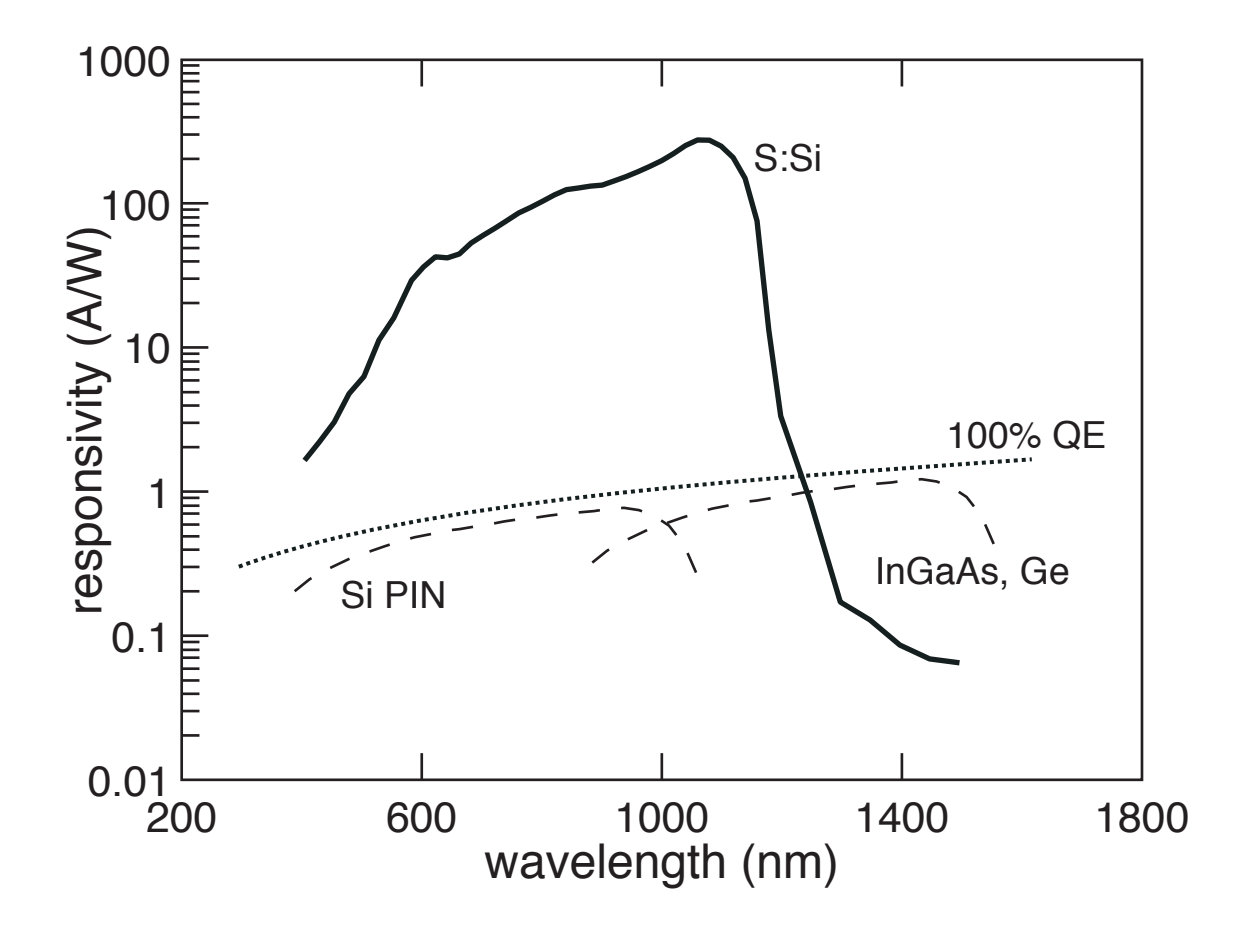
responsivity



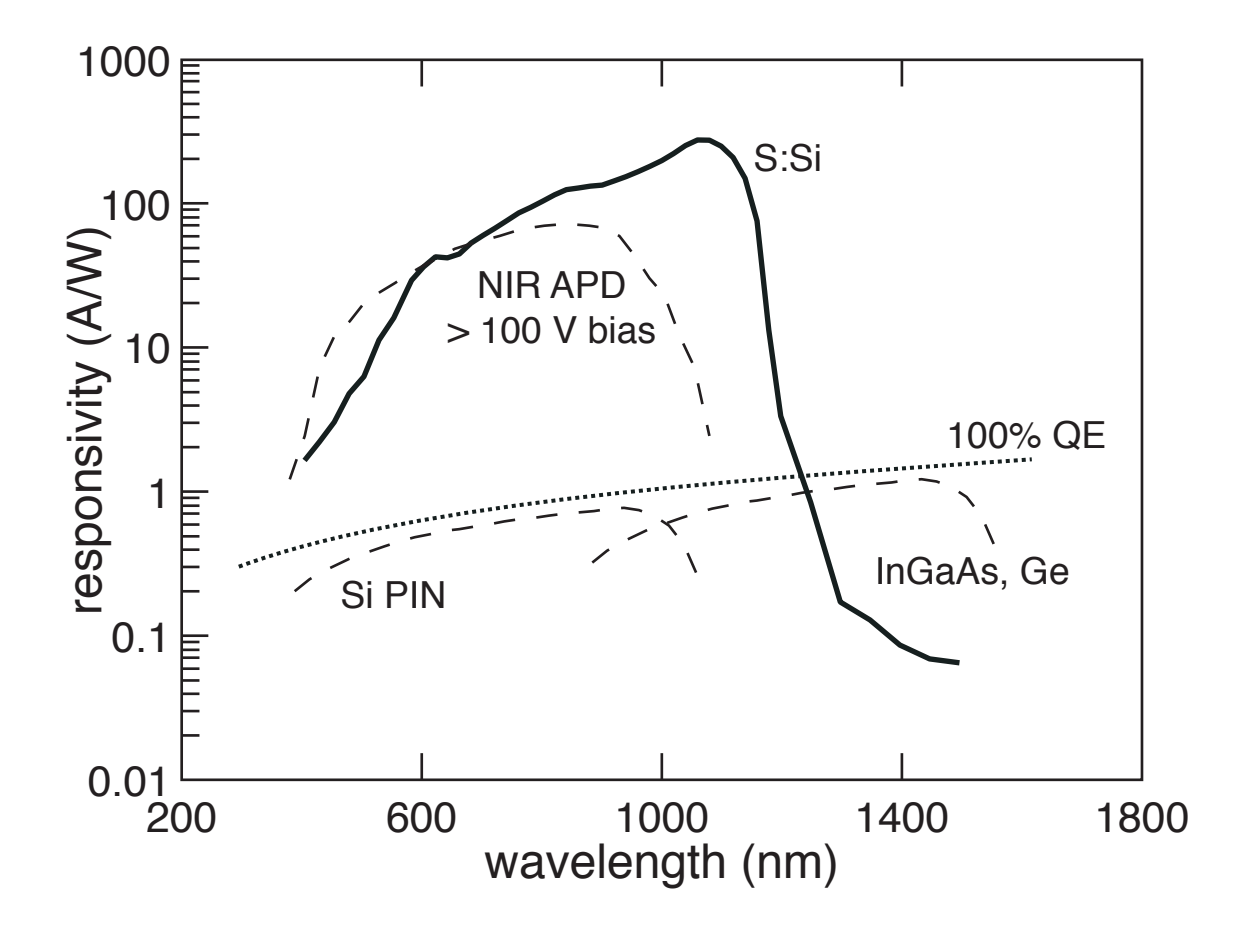
responsivity



responsivity



responsivity



- enhanced sensitivity
- extended IR response

near-IR is next wave in imaging!

gesture recognition

image: fastcolabs.com

1 properties 2 intermediate band 3 devices

1 properties 2 intermediate band 3 devices

biometrics

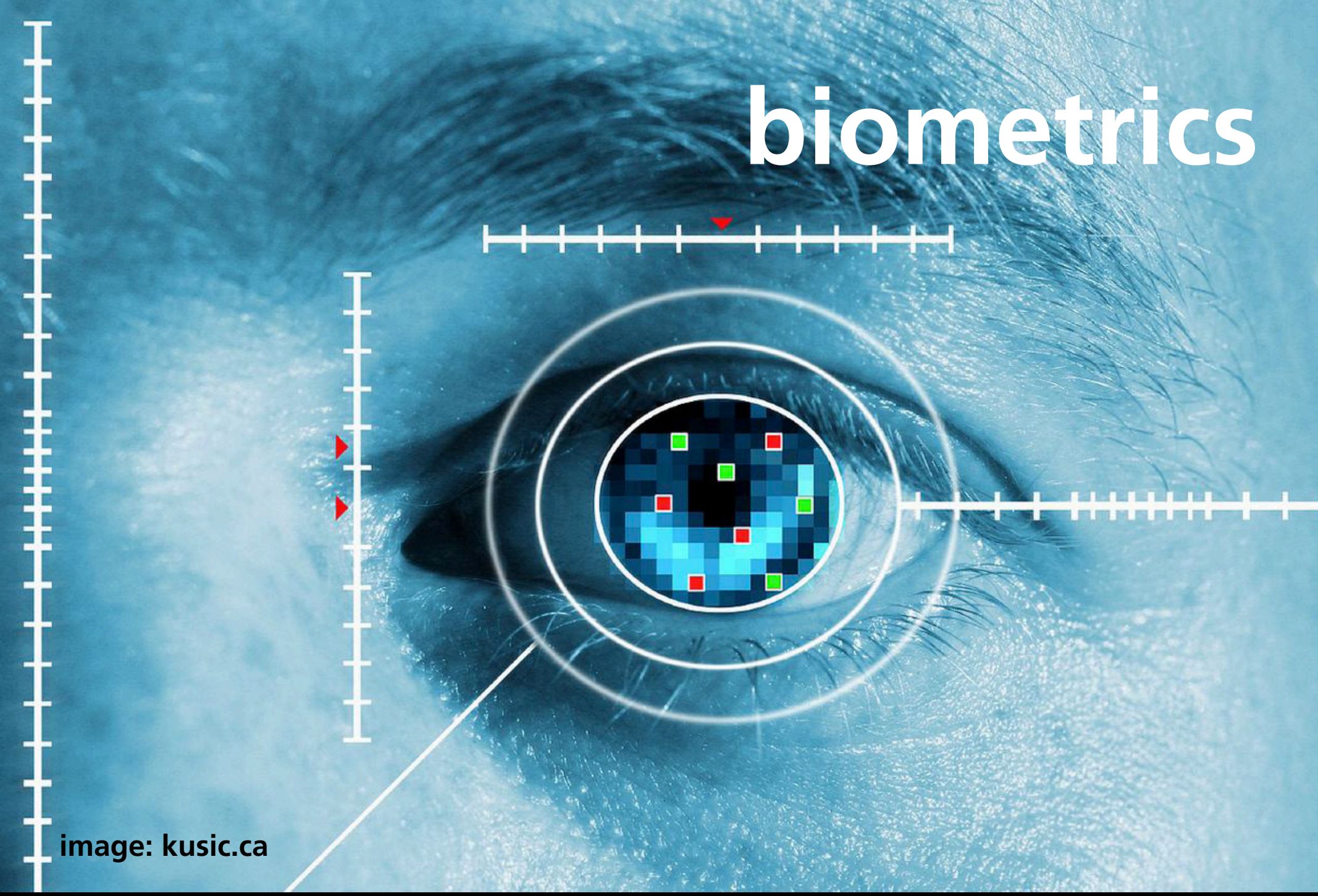


image: kusic.ca

1 properties

2 intermediate band

3 devices

robotics

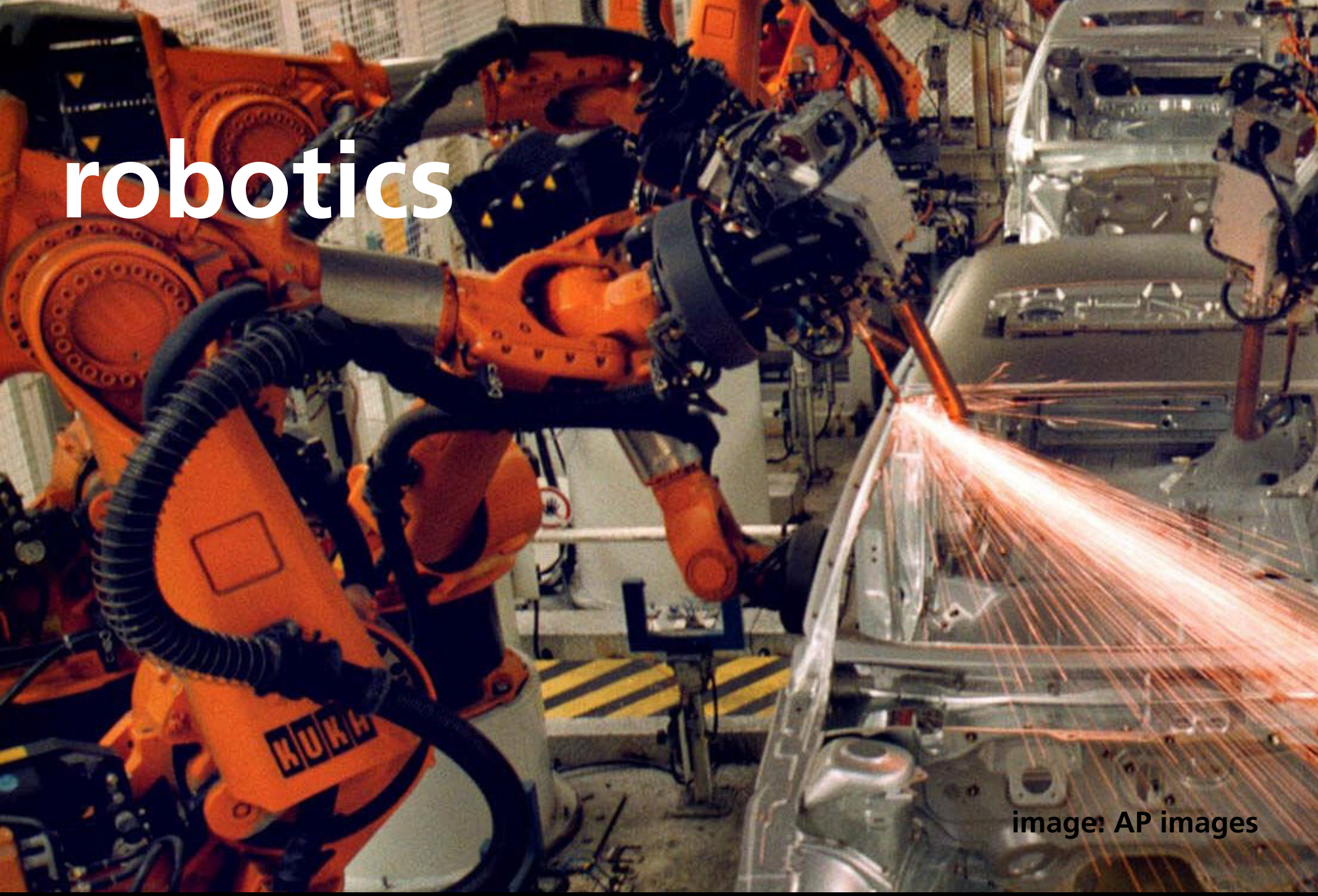
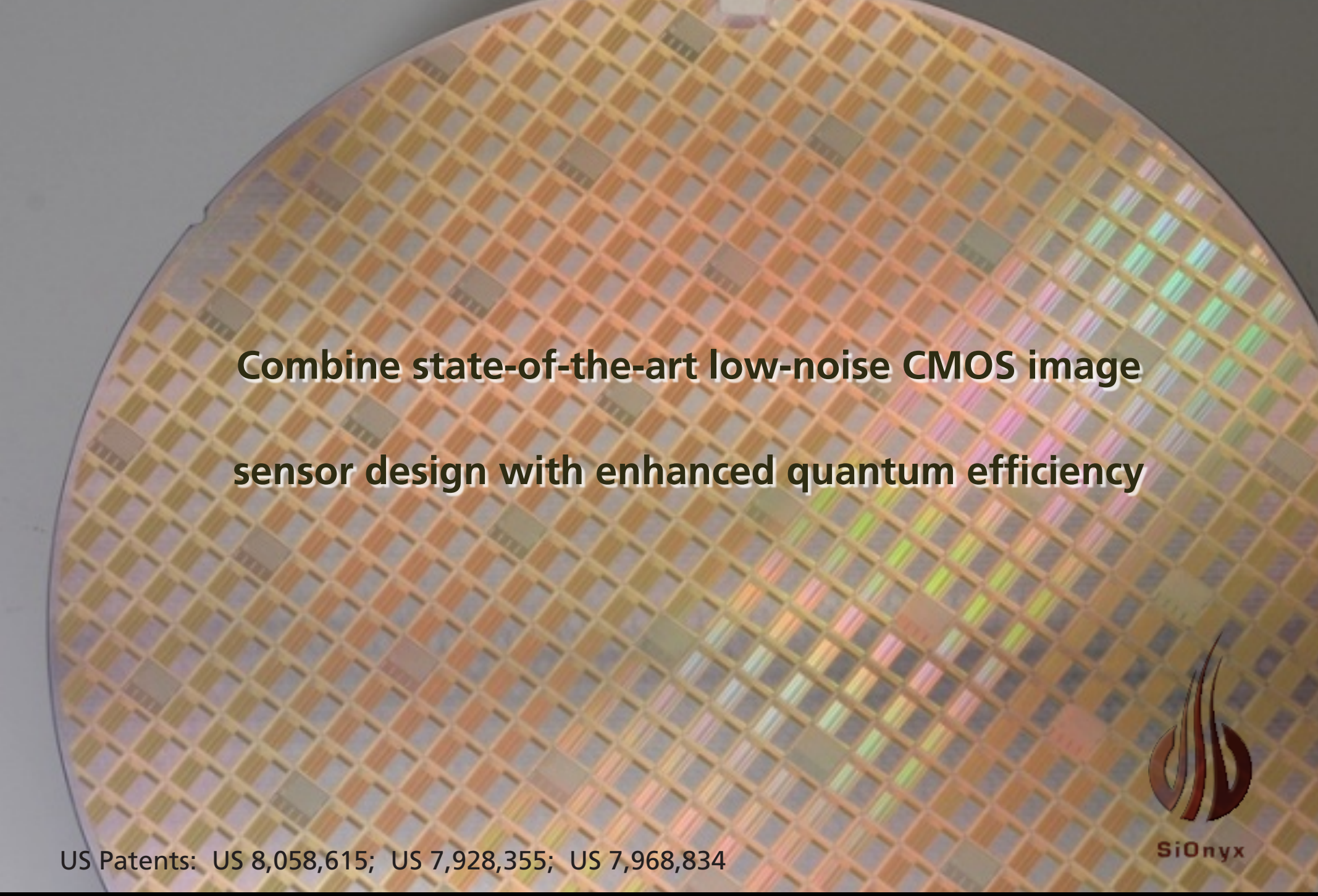


image: AP images

1 properties 2 intermediate band 3 devices

1 properties 2 intermediate band 3 devices

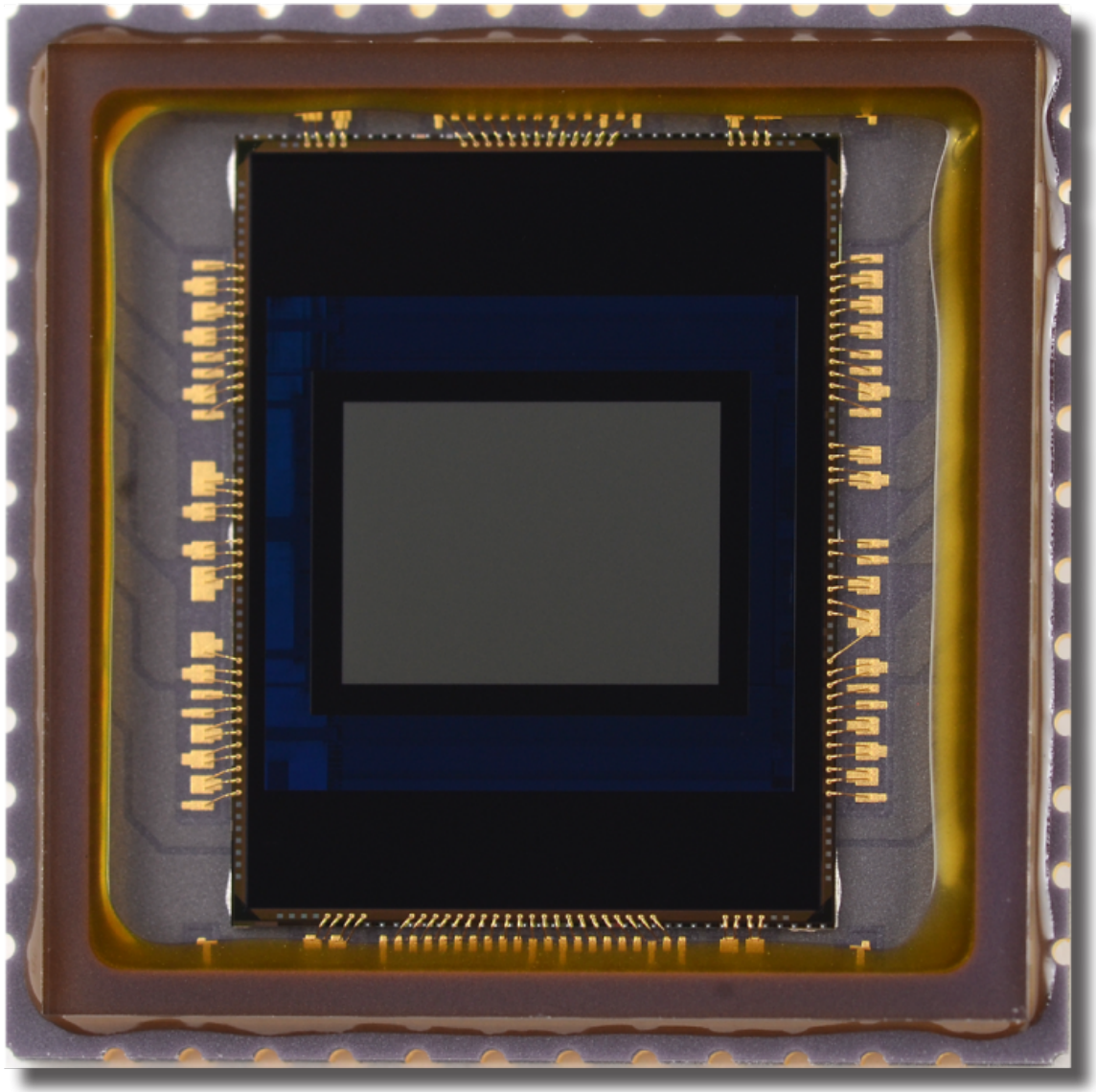


Combine state-of-the-art low-noise CMOS image sensor design with enhanced quantum efficiency

US Patents: US 8,058,615; US 7,928,355; US 7,968,834

SiOnyx

1 properties 2 intermediate band 3 devices



SiOnyx

US Patents: US 8,058,615; US 7,928,355; US 7,968,834

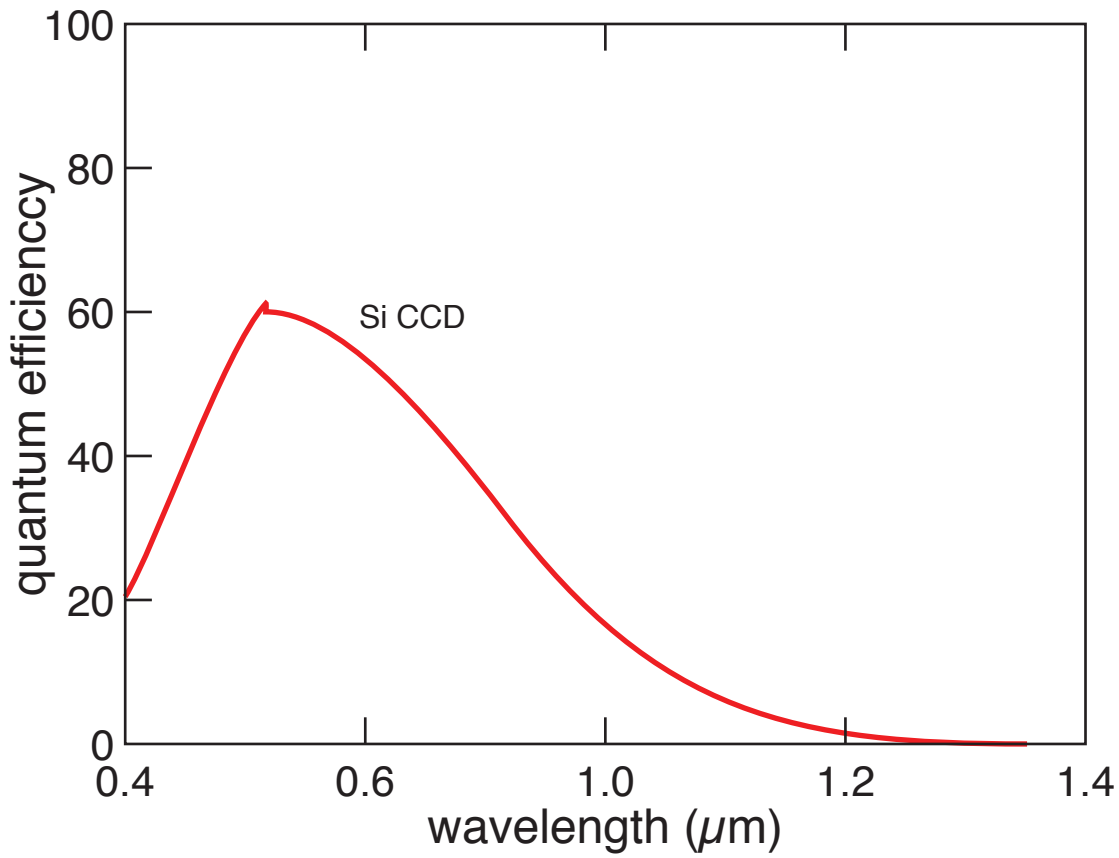
1 properties 2 intermediate band 3 devices

Resolution	pixel (μm)	noise (e/pix)	I_{dark} (e/pix/s)	P (mW)
872 x 654	5.6	2.1	24	300
1280 x 720	5.6	2.1	24	360
1280 x 1024	10	2.6	83	400

8” CIS process flow

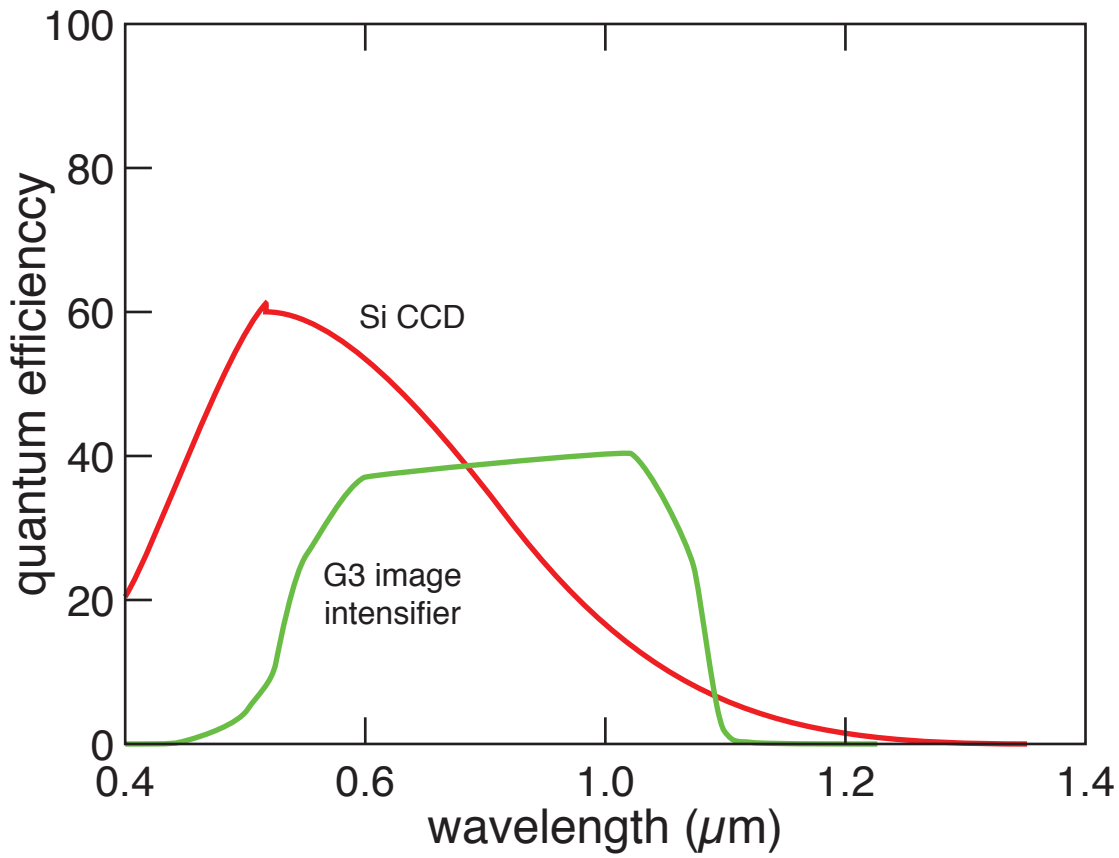
4T pixel architecture

SiOnyx

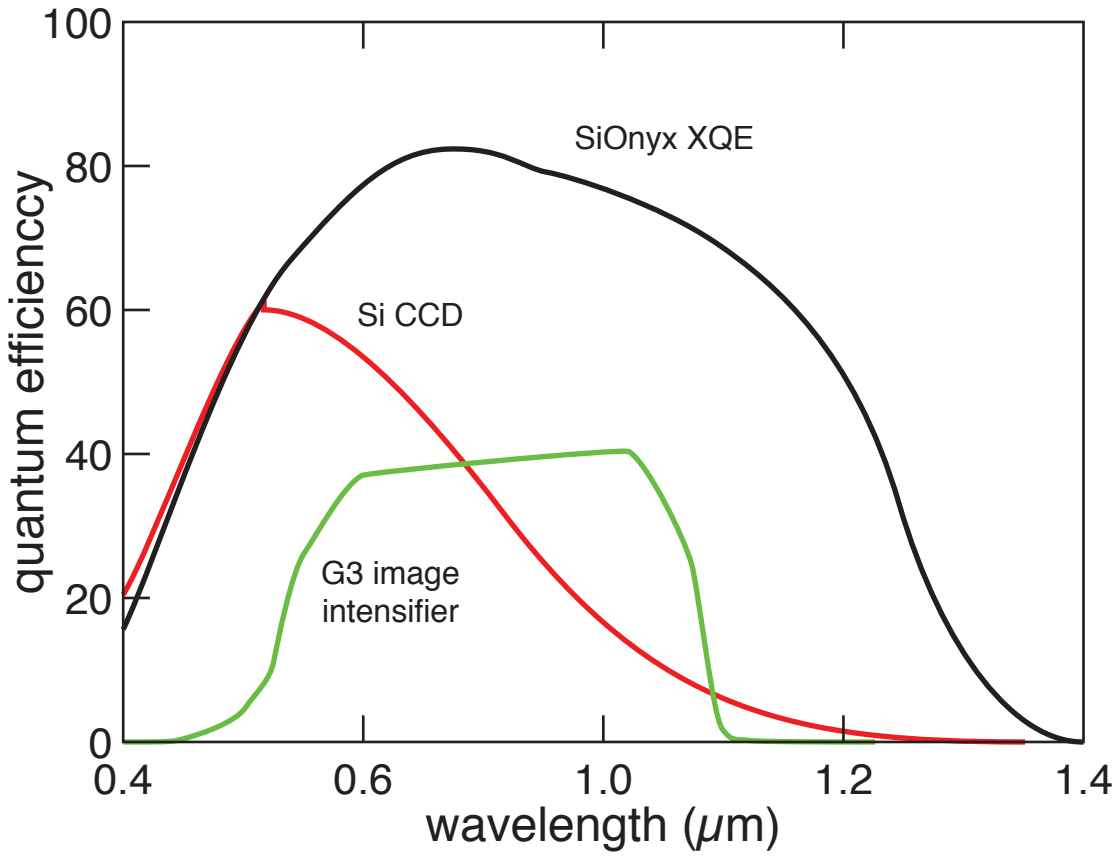


SiOnyx

1 properties 2 intermediate band 3 devices

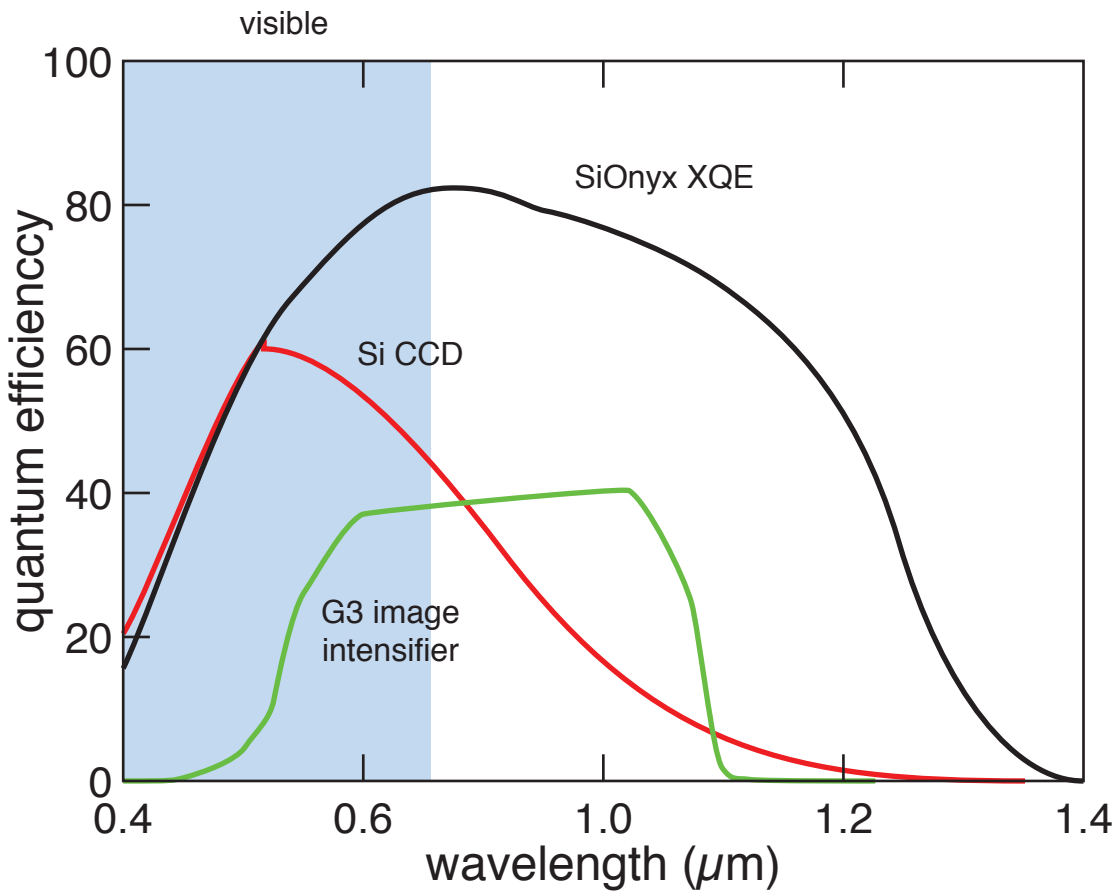

100
80
60
40
20
0
quantum efficienccy
Si CCD
G3 image
intensifier
0.4
0.6
1.0
1.2
1.4
wavelength (μm)

SiOnyx



SiOnyx

1 properties 2 intermediate band 3 devices



SiOnyx

1 properties 2 intermediate band 3 devices

no compromises in visible

Sony color CCD

SiOnyx

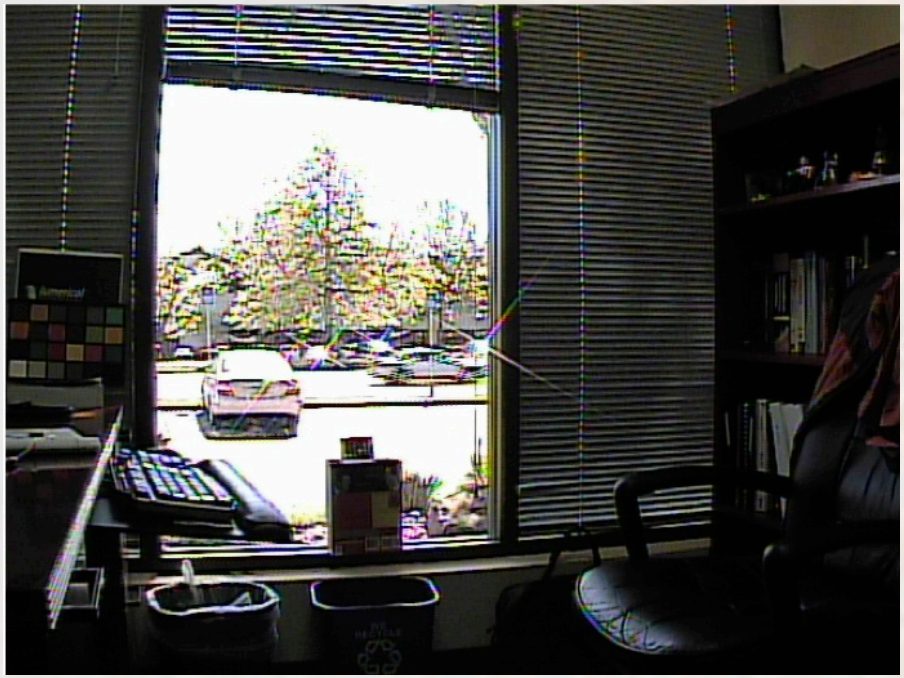
no compromises in visible

Sony color CCD

SiOnyx XQE sensor

SiOnyx

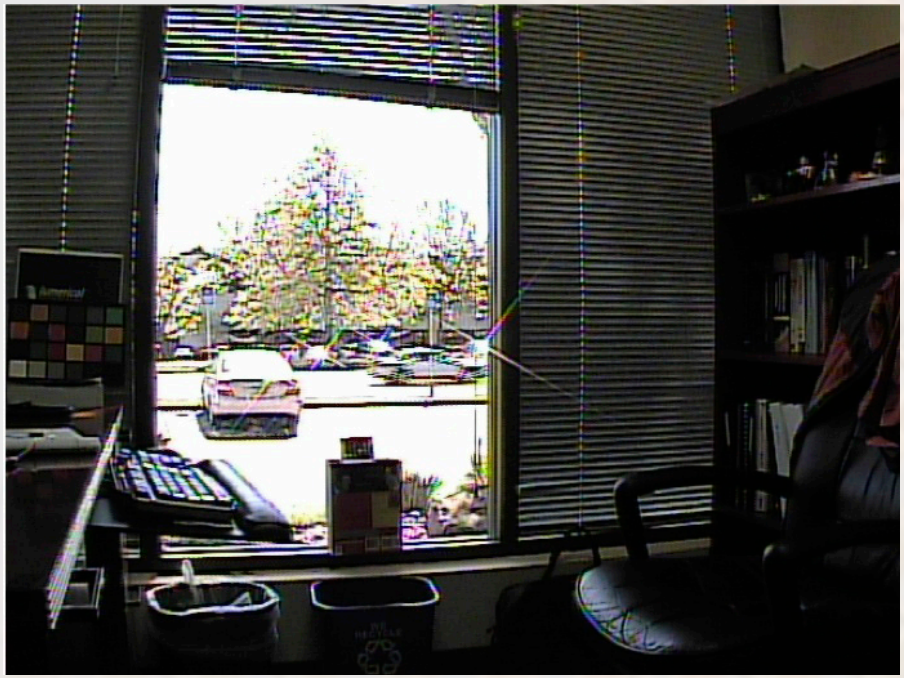
90+ dB dynamic range



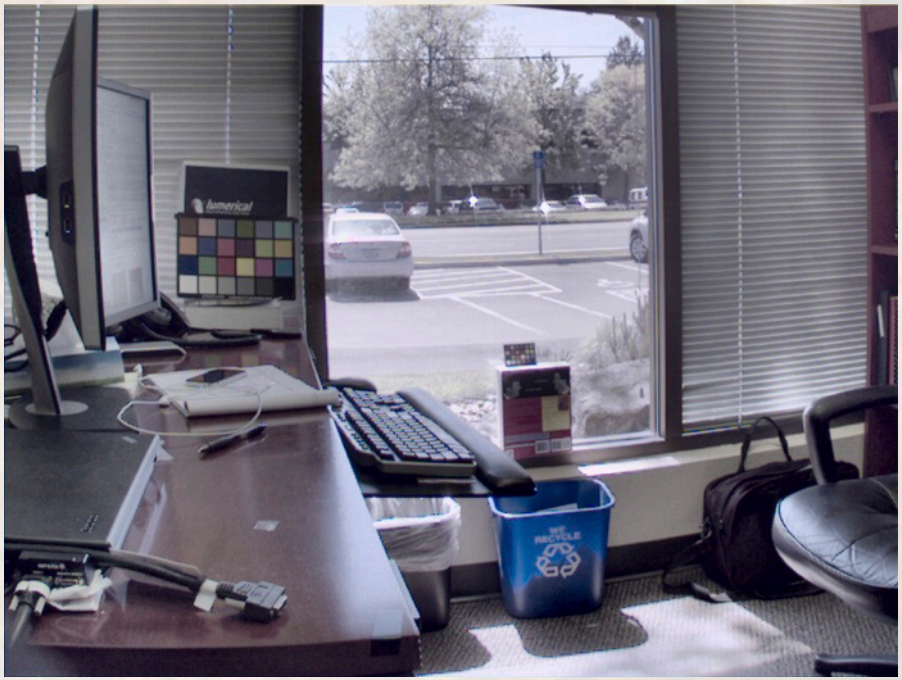
Sony color CCD

SiOnyx

90+ dB dynamic range



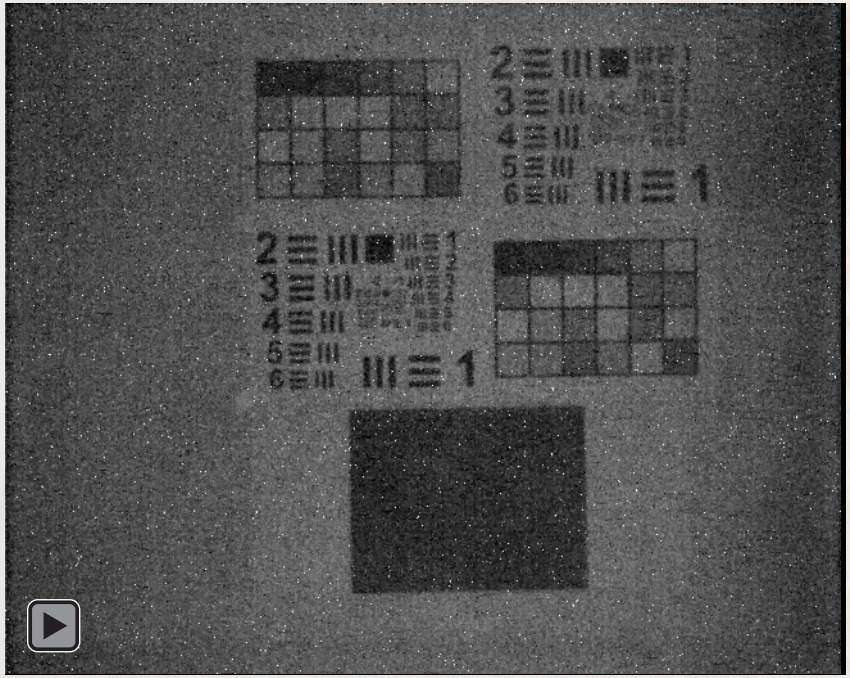
Sony color CCD



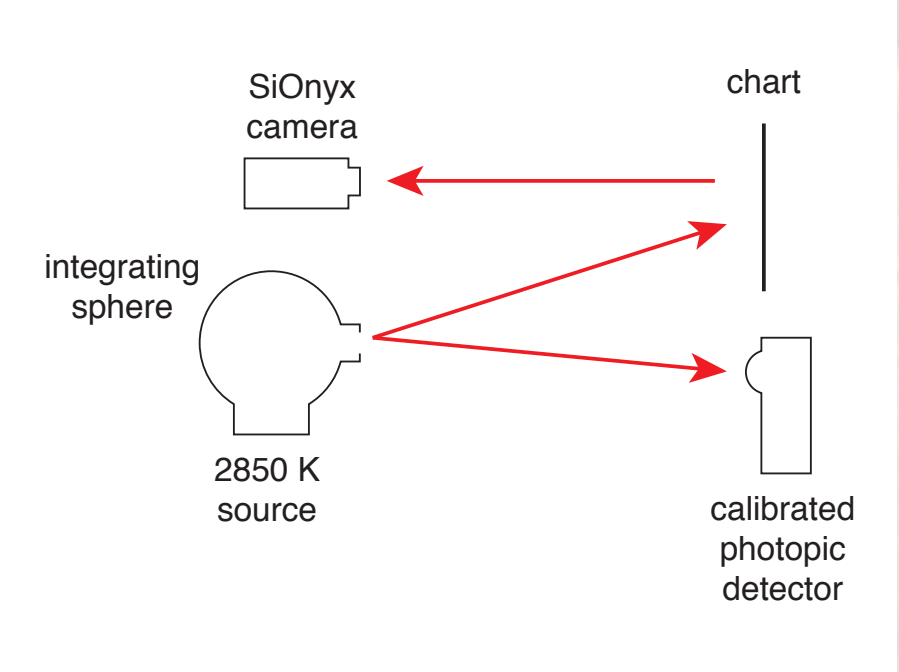
SiOnyx X1 sensor

SiOnyx

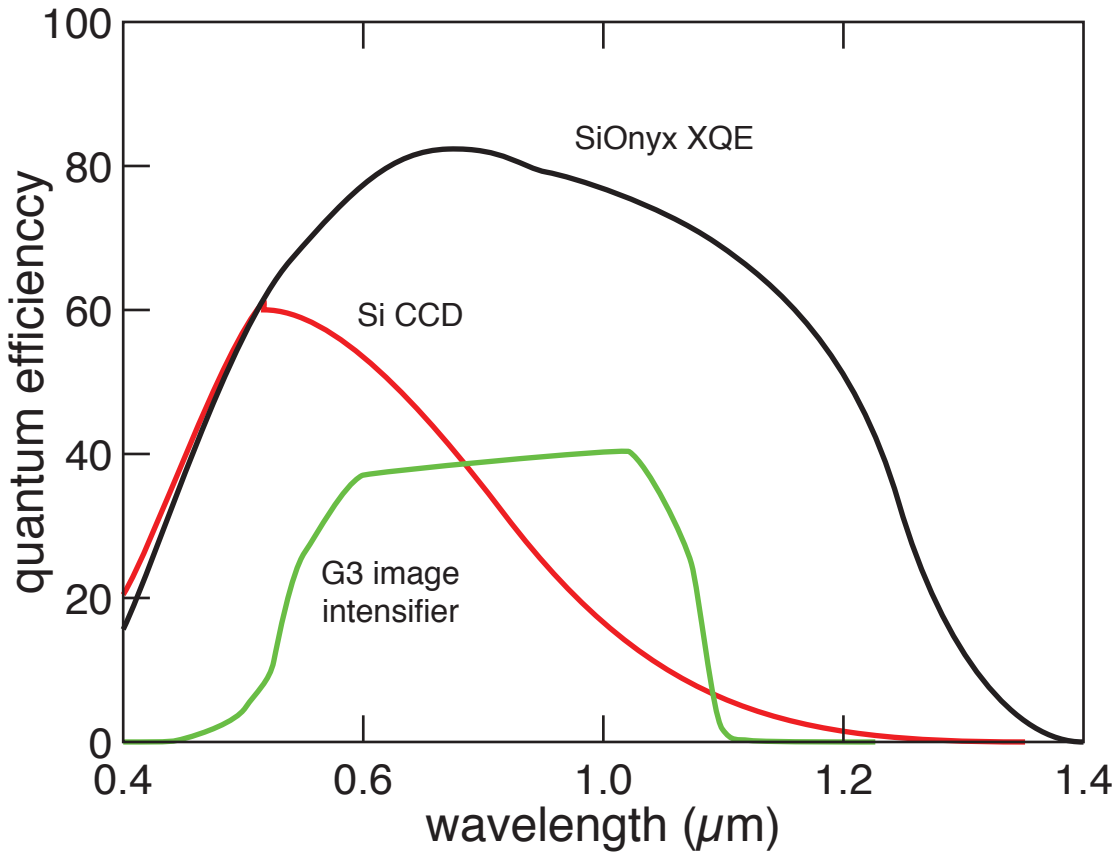
0.9 mlux irradiance from 2850 K source



SiOnyx (50 mm, F1.4, 30 fps)

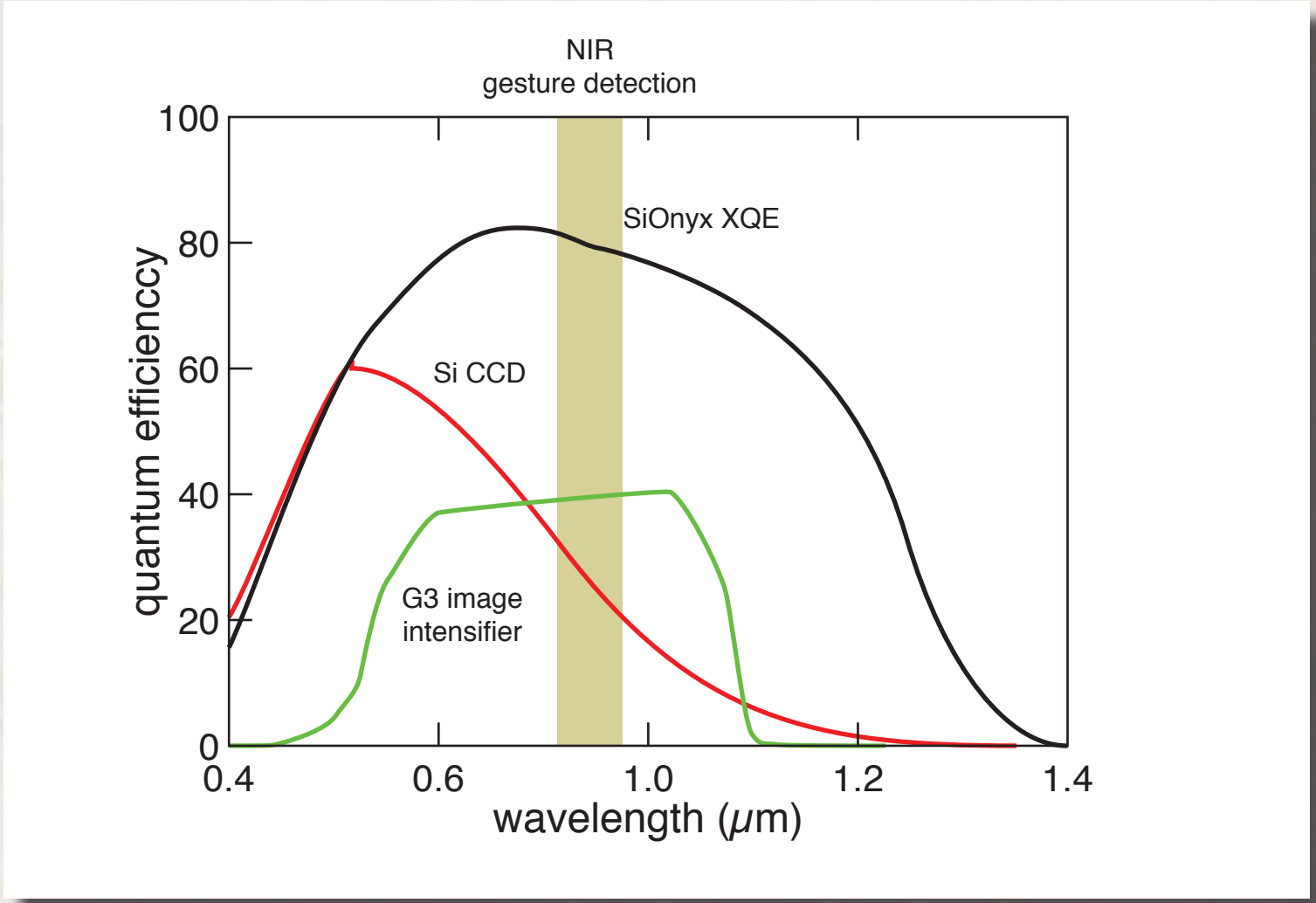


SiOnyx



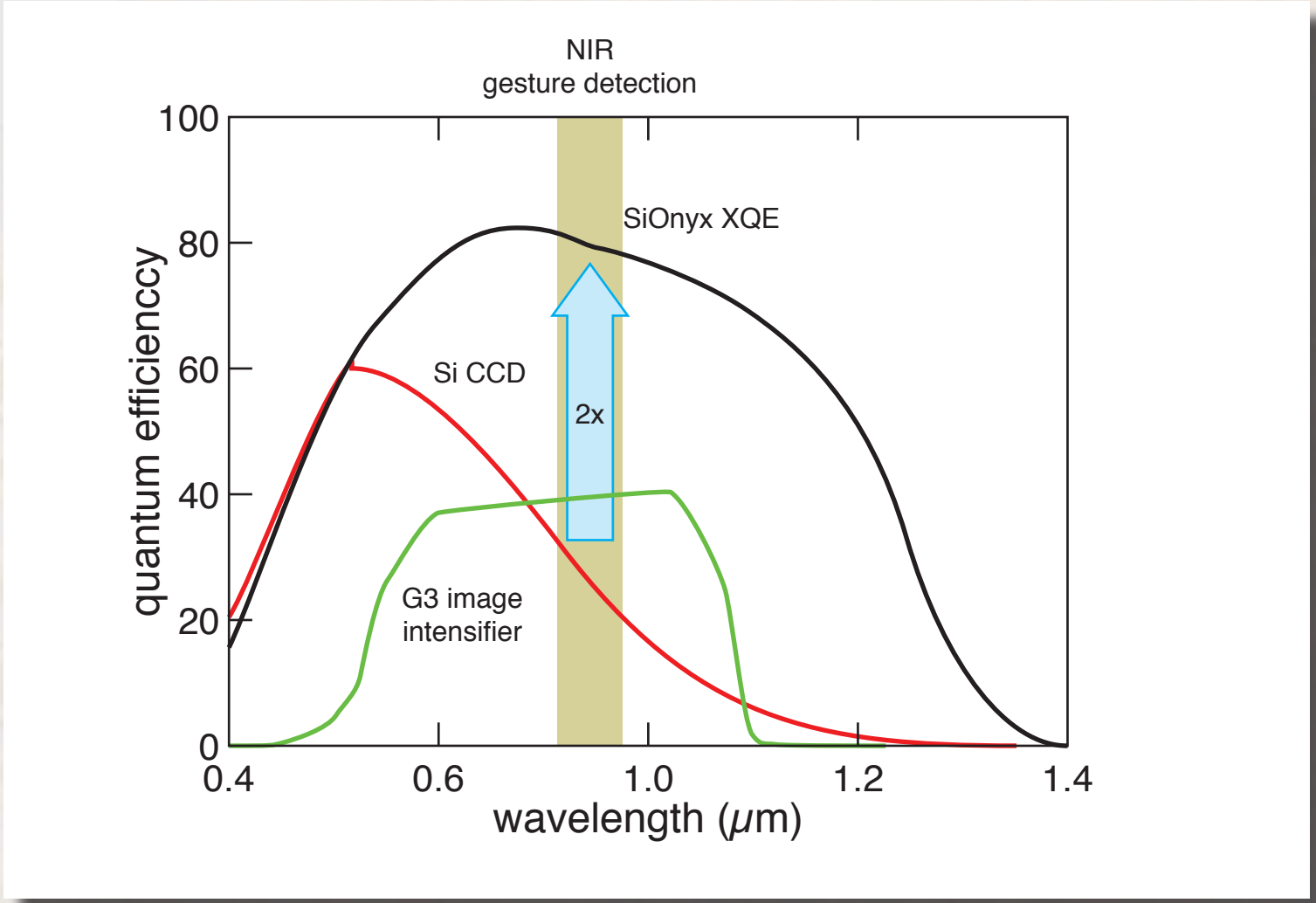
SiOnyx

1 properties 2 intermediate band 3 devices



SiOnyx

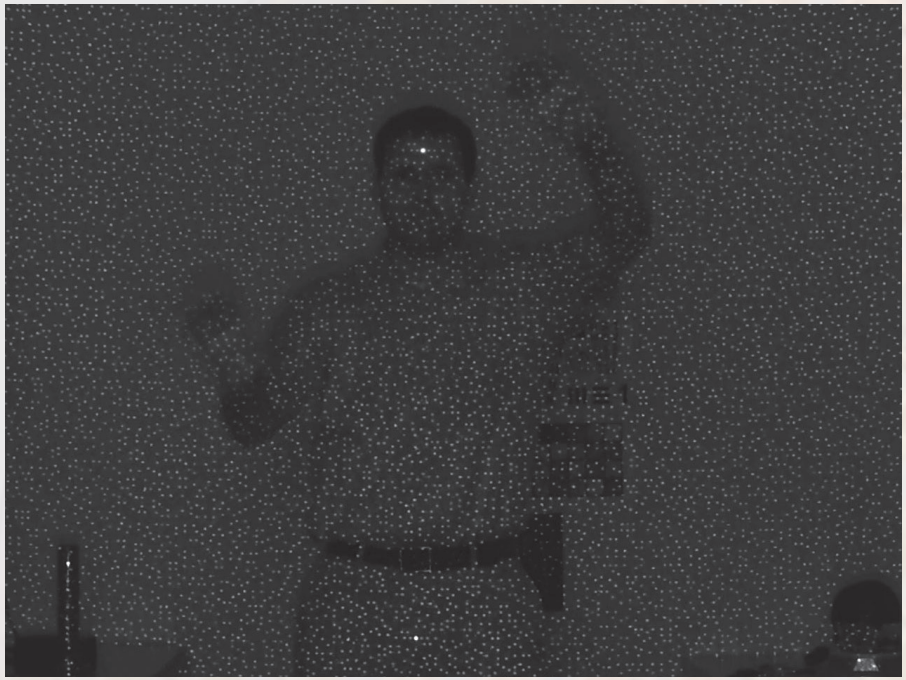
1 properties 2 intermediate band 3 devices



SiOnyx

1 properties 2 intermediate band 3 devices

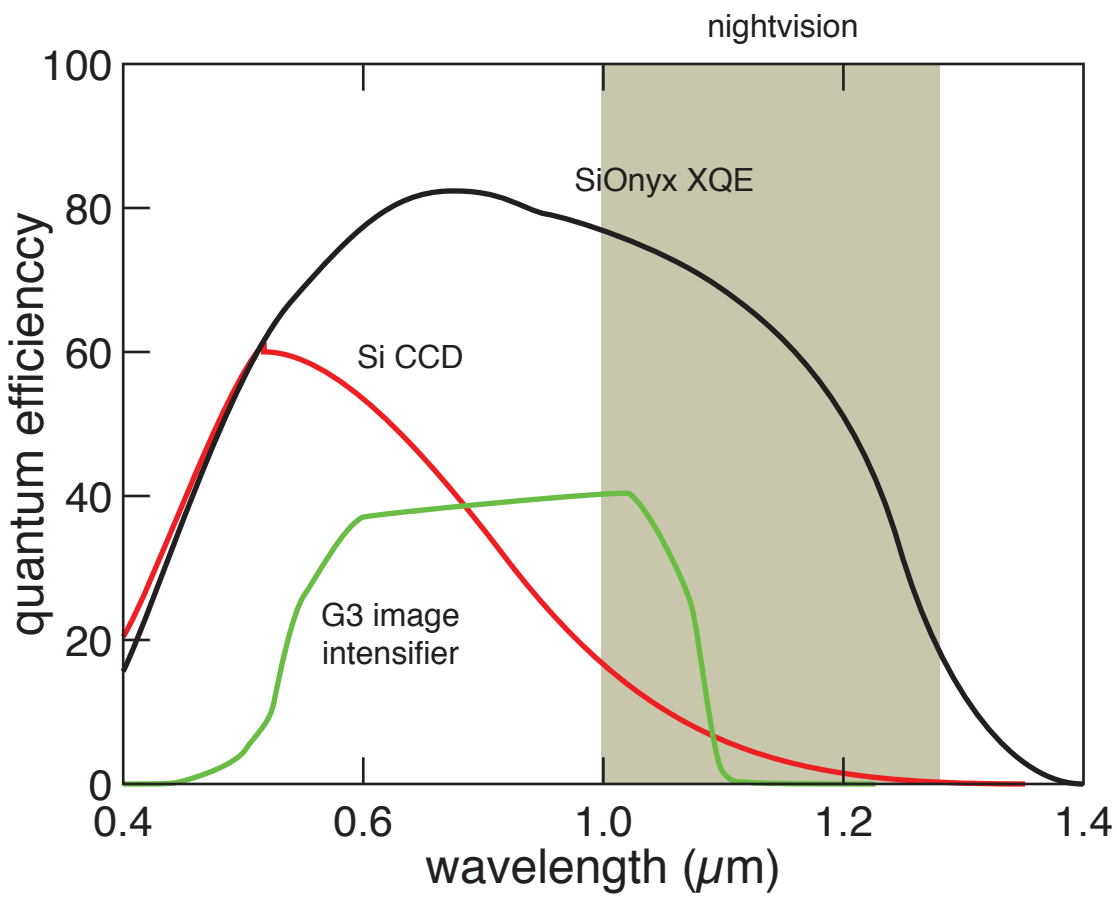
3D imaging for gesture user interface (850 nm)



SiOnyx XQE

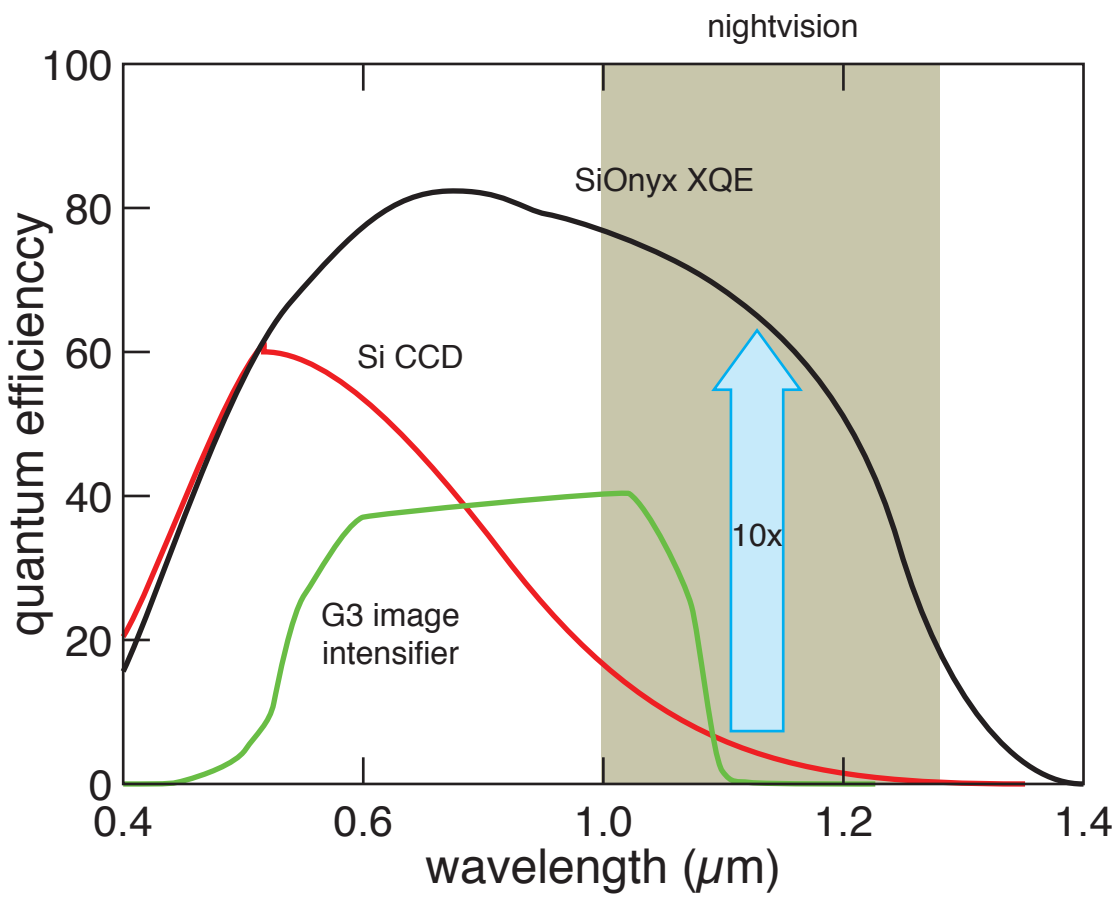
standard CCD

SiOnyx



SiOnyx

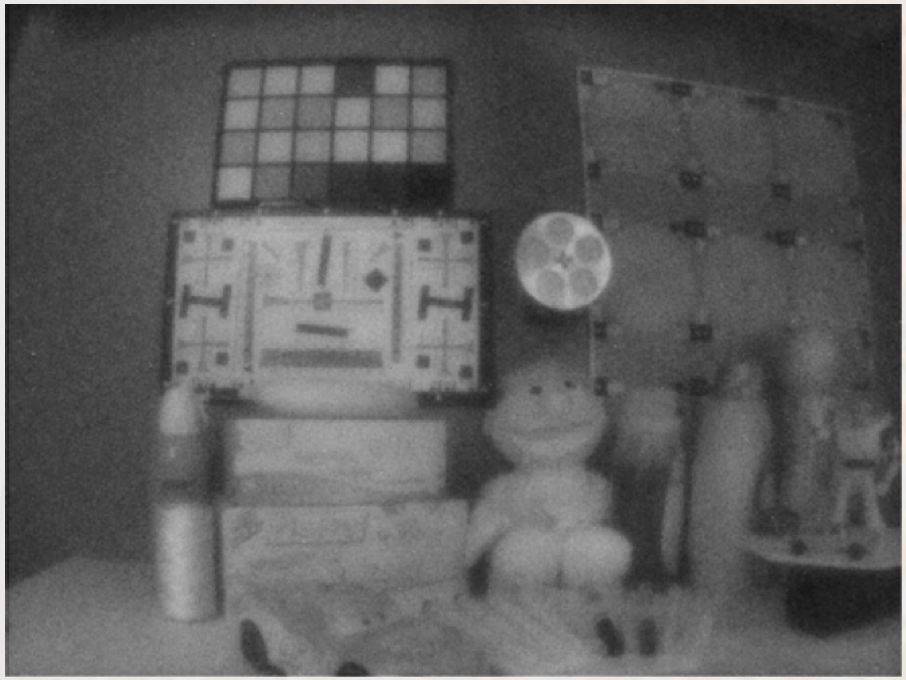
1 properties 2 intermediate band 3 devices



SiOnyx

1 properties 2 intermediate band 3 devices

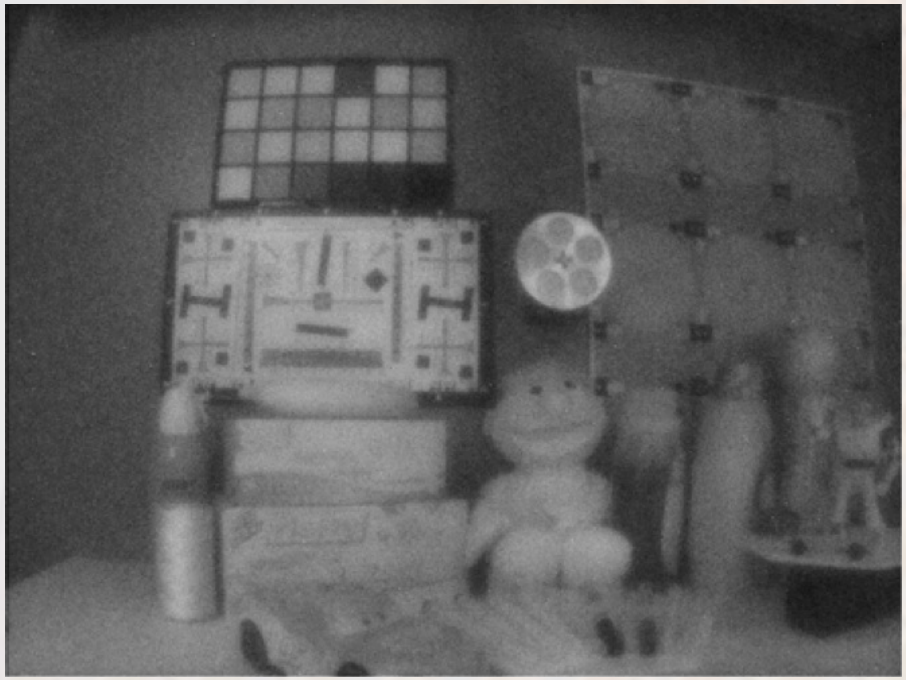
dark room 1050 illumination



SiOnyx (F1.4, 33 ms, 24x)

SiOnyx

dark room 1050 illumination

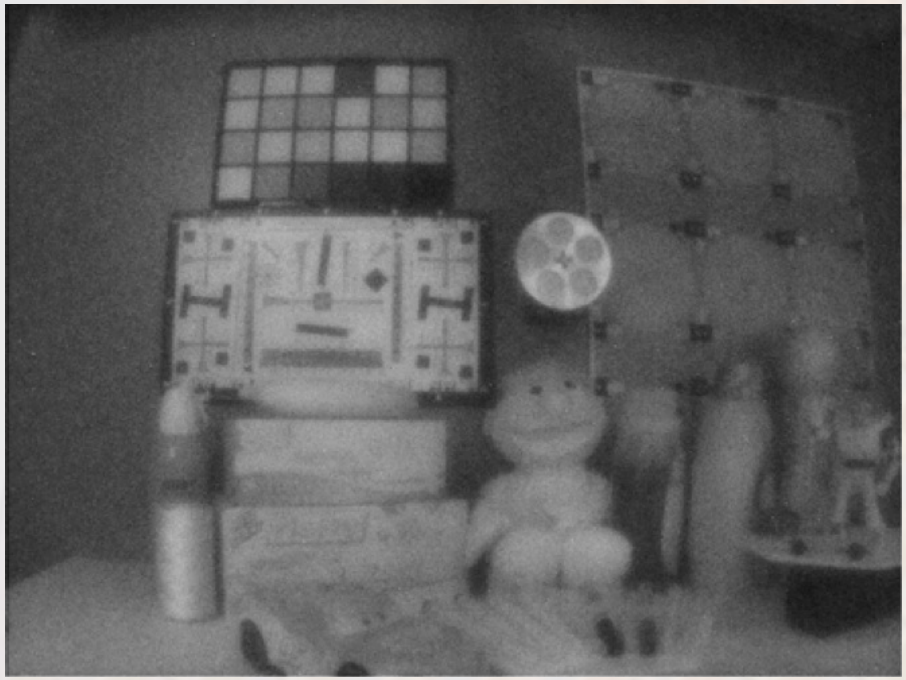


SiOnyx (F1.4, 33 ms, 24x)

reference (F1.4, 33 ms, 24x)

SiOnyx

dark room 1050 illumination



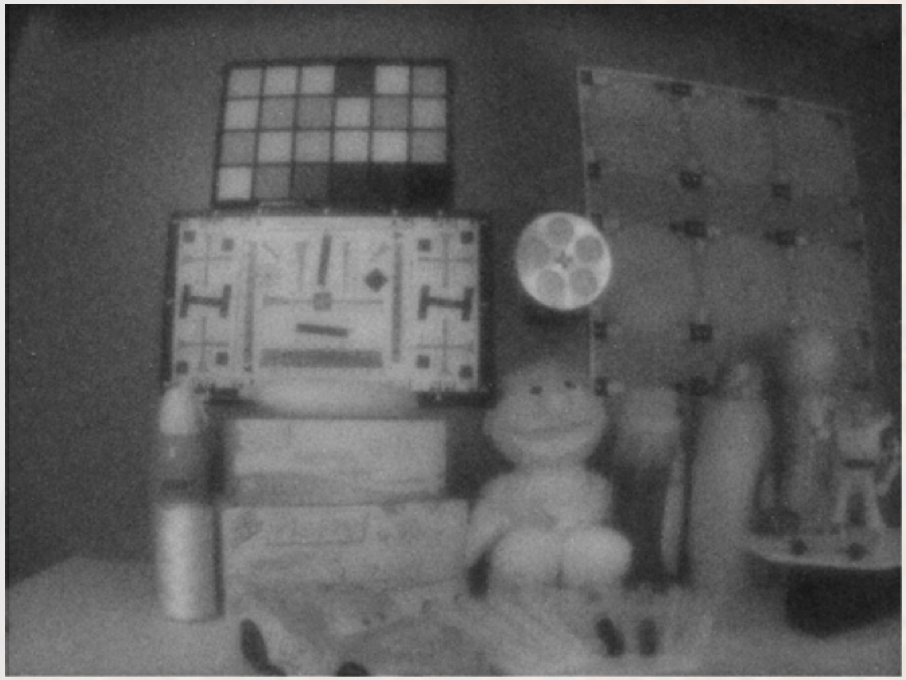
SiOnyx (F1.4, 33 ms, 24x)

reference (F1.4, 33 ms, 24x)

no image processing

SiOnyx

dark room 1050 illumination

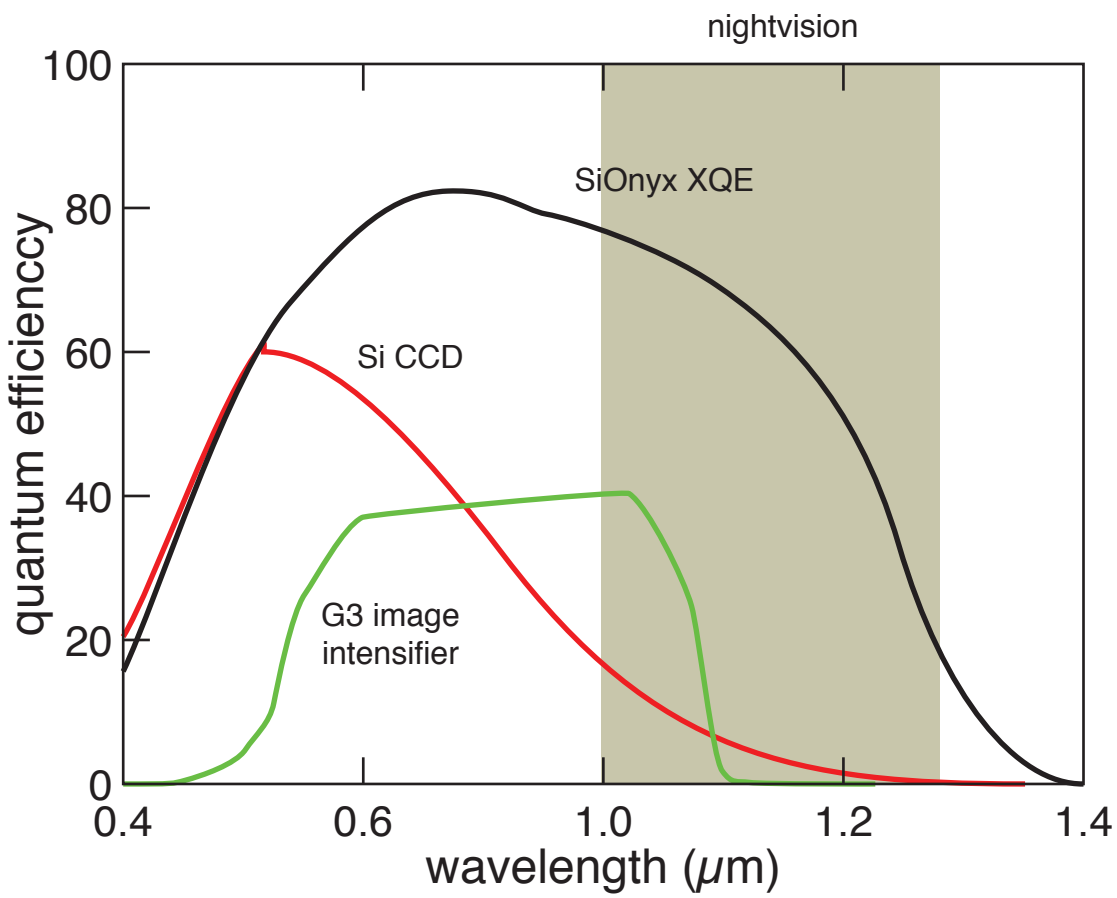


SiOnyx (F1.4, 33 ms, 24x)

reference (F1.4, 33 ms, 24x)
2x DIGITAL GAIN ADDED

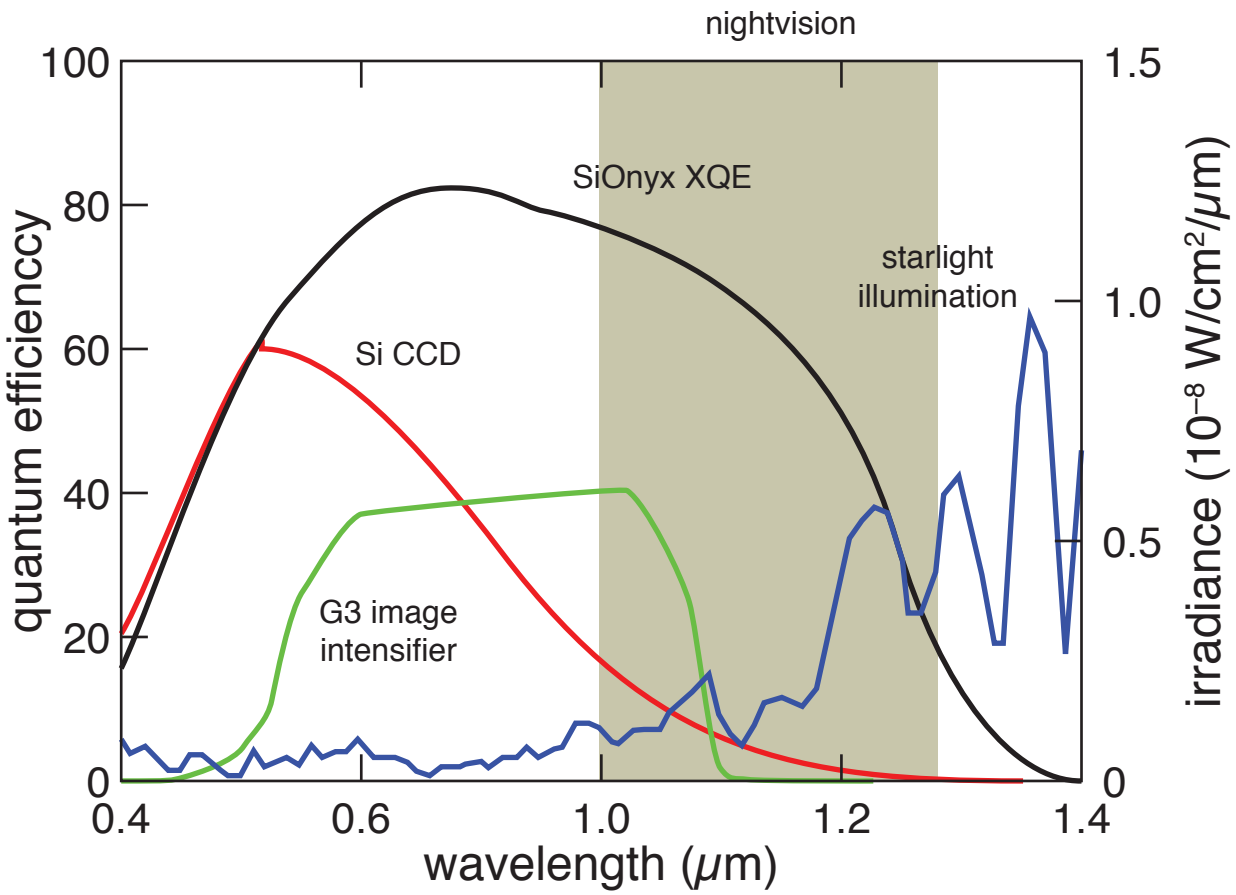
no image processing

SiOnyx



SiOnyx

1 properties 2 intermediate band 3 devices



SiOnyx

1 properties 2 intermediate band 3 devices

starlight illumination

SiOnyx
25 mm
F1.4
30 fps

clear, moonless night (laser targeting spot: 30 μJ at 100 m)

SiOnyx

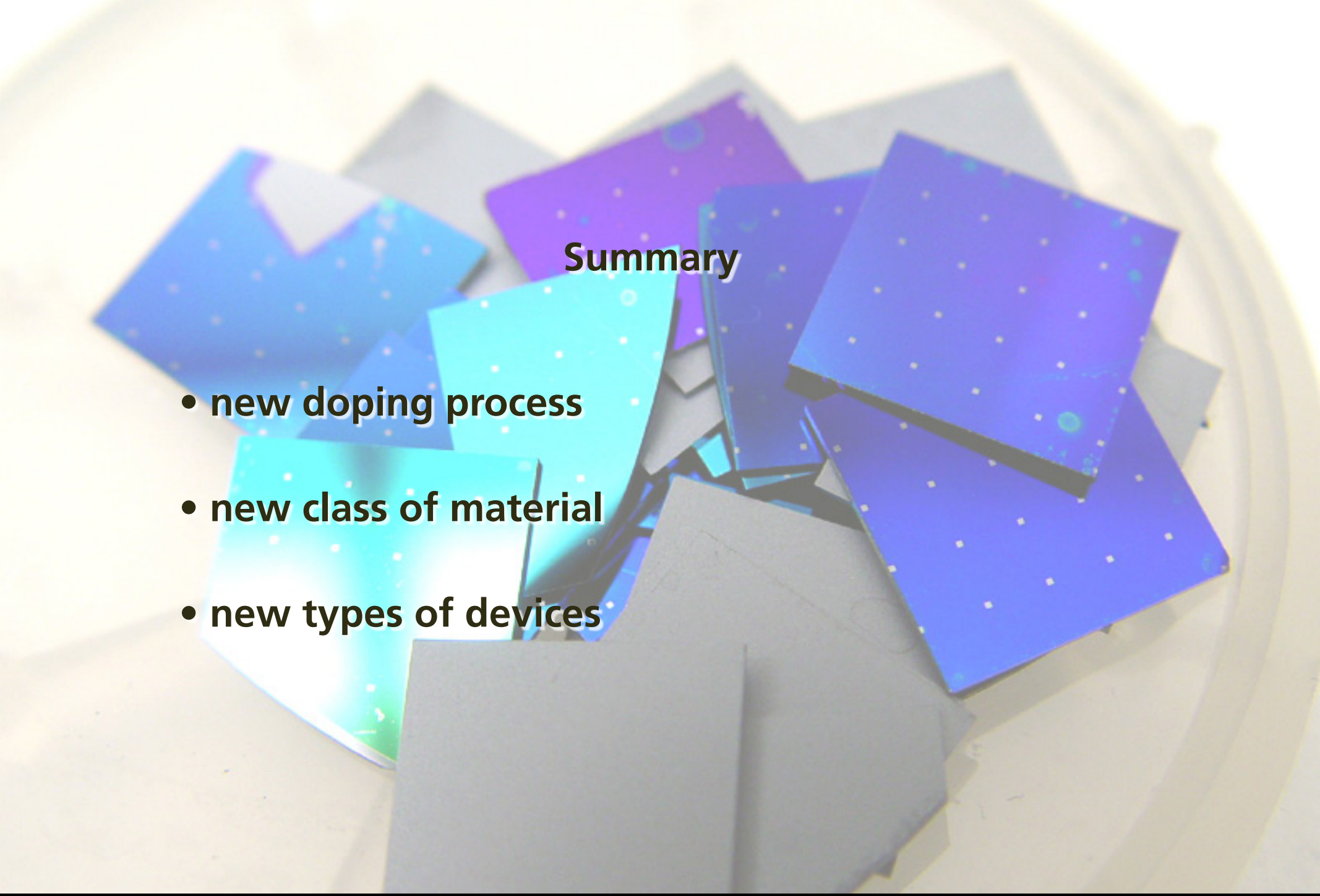
Things to keep in mind

- can turn absorption into carrier generation
- very high responsivity in VIS and NIR

Things to keep in mind

- can turn absorption into carrier generation
- very high responsivity in VIS and NIR

disruptive improvement in Si imaging



Summary

- new doping process
- new class of material
- new types of devices

Funding:

Army Research Office
DARPA
Department of Energy
NDSEG
National Science Foundation

for more information and a copy of this presentation:

mazur.harvard.edu

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