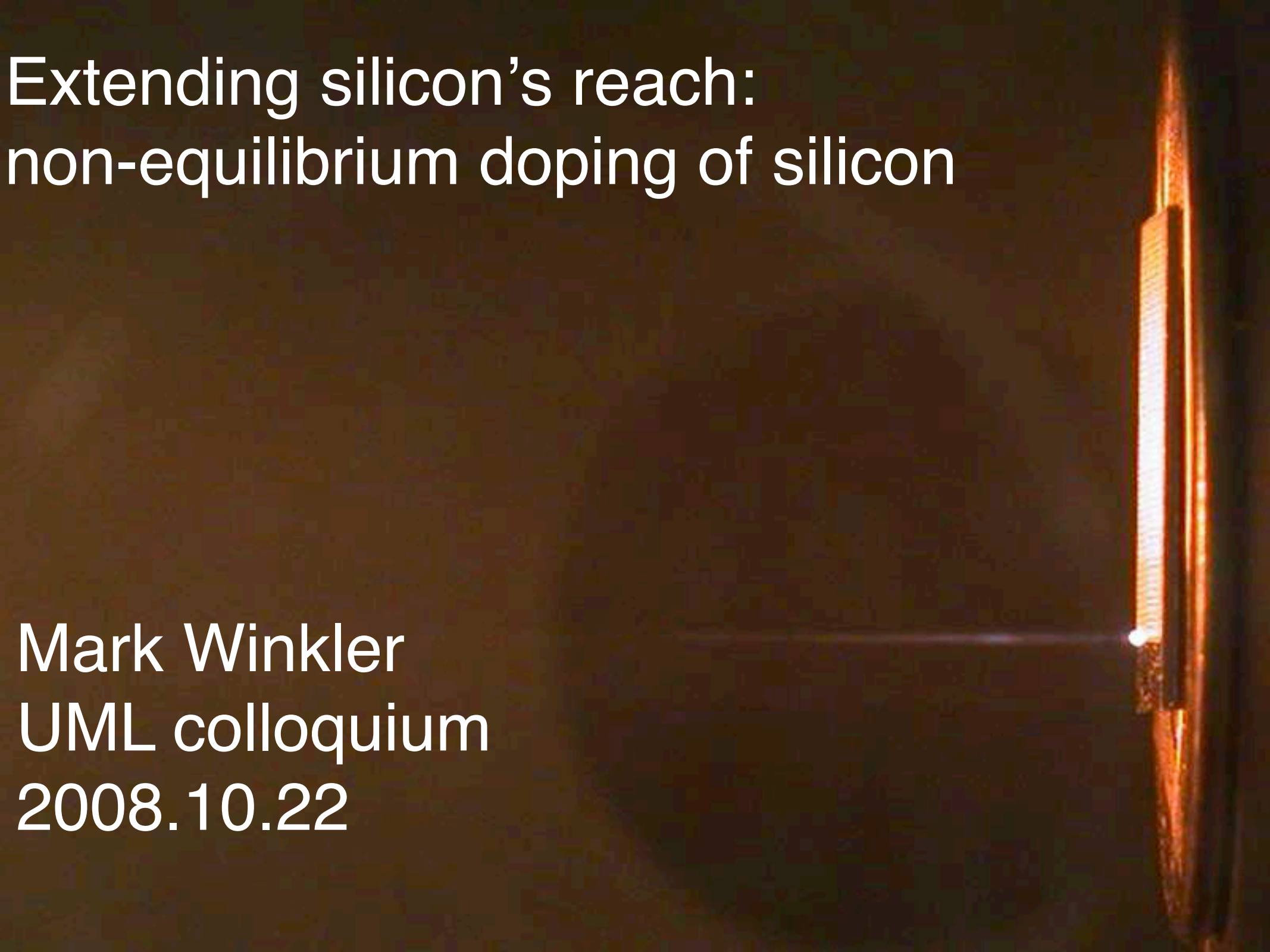
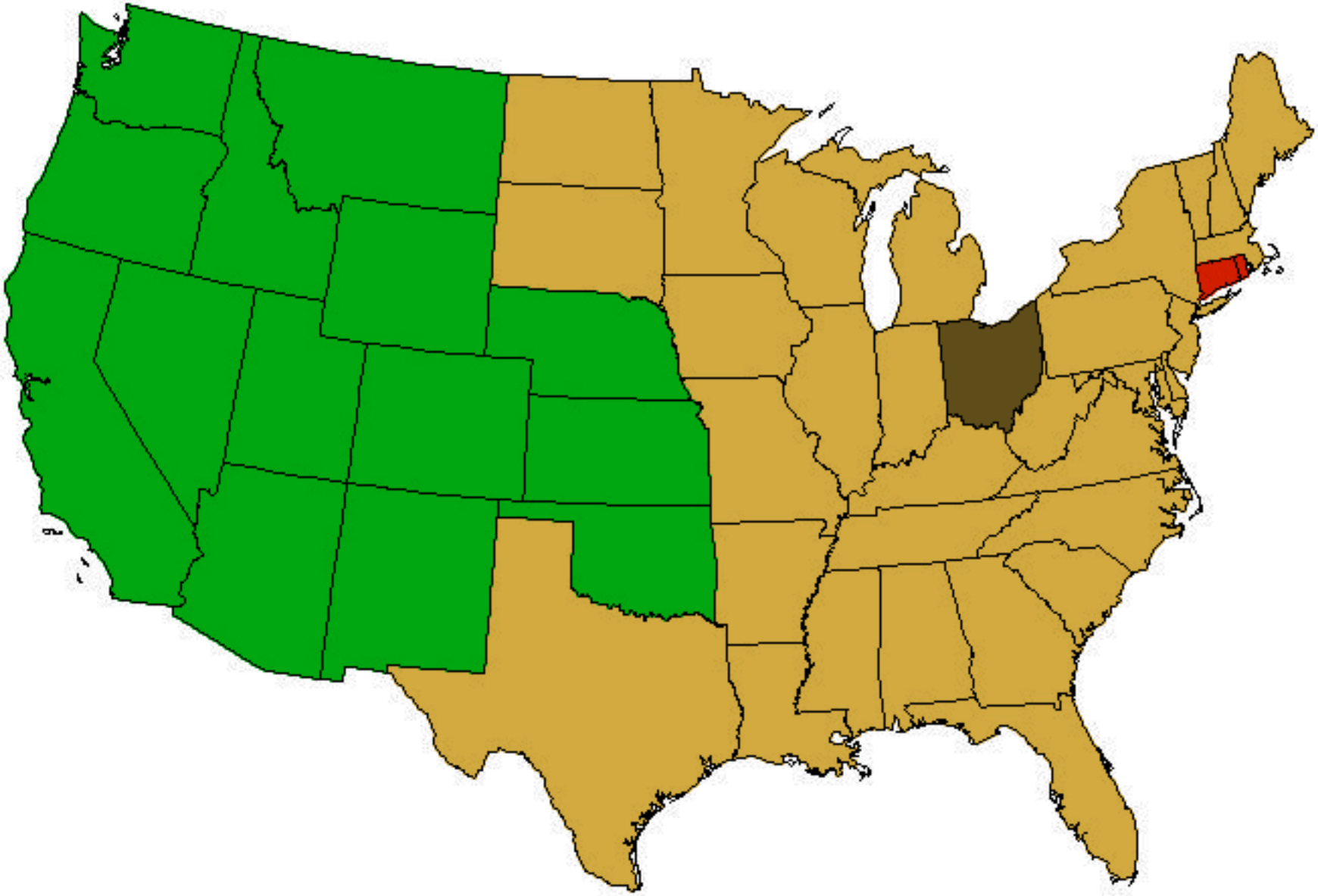
Extending silicon's reach: non-equilibrium doping of silicon

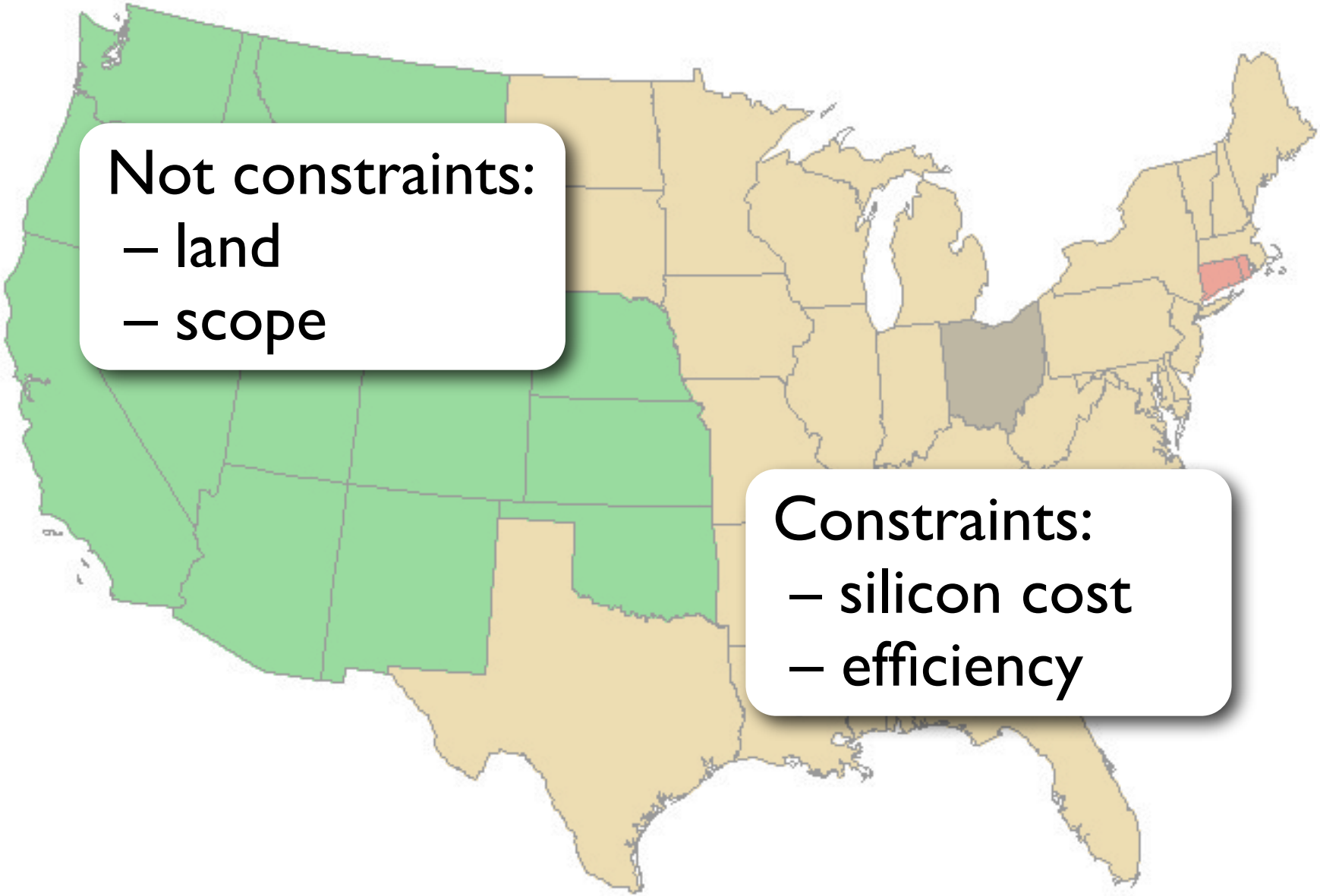


Mark Winkler
UML colloquium
2008.10.22

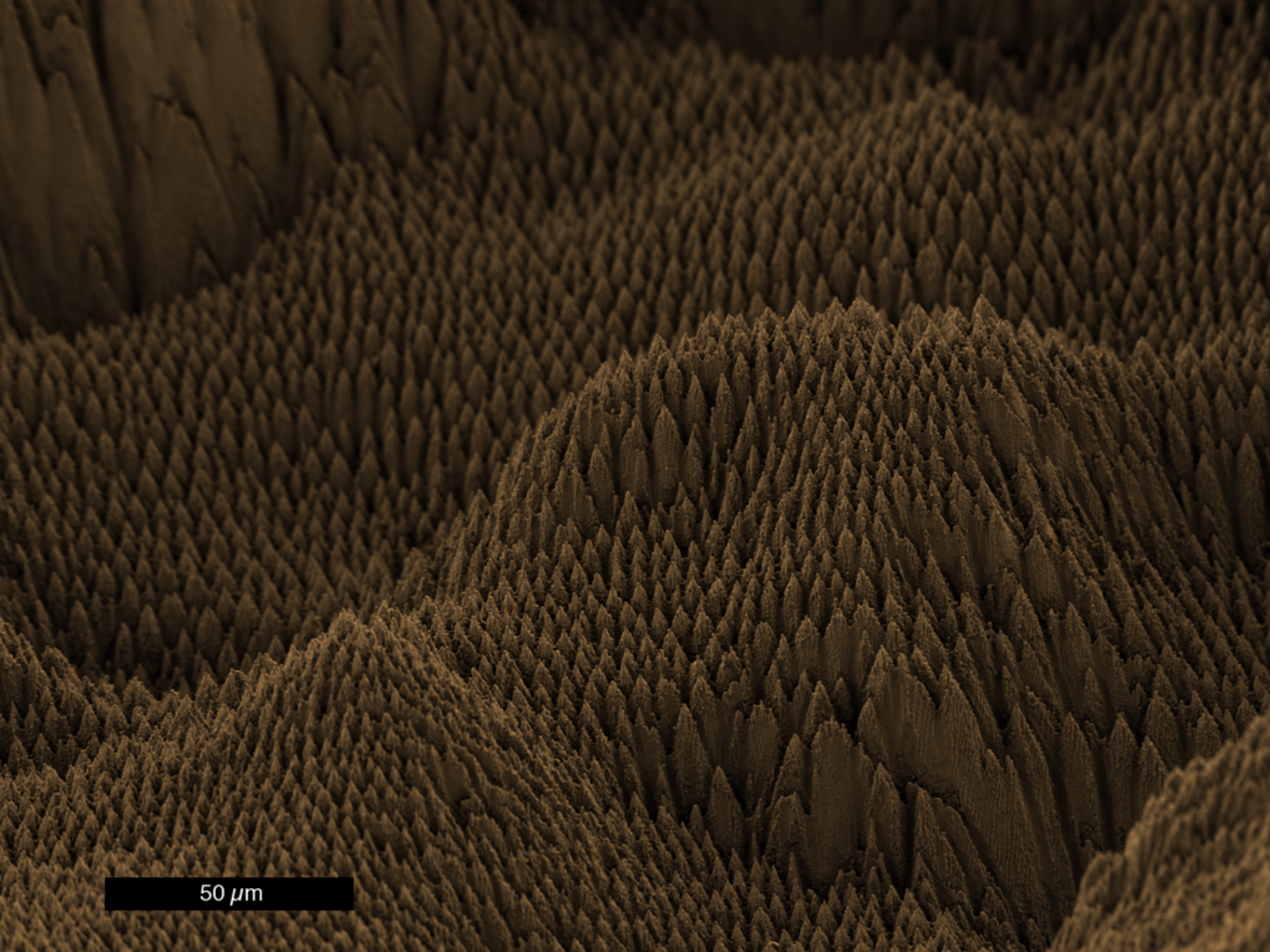
Why extend silicon's reach?



Why extend silicon's reach?




100 μm


50 μm

Understanding a material that extends silicon's reach:

Understanding a material that extends silicon's reach:

- What we know about laser doping of silicon

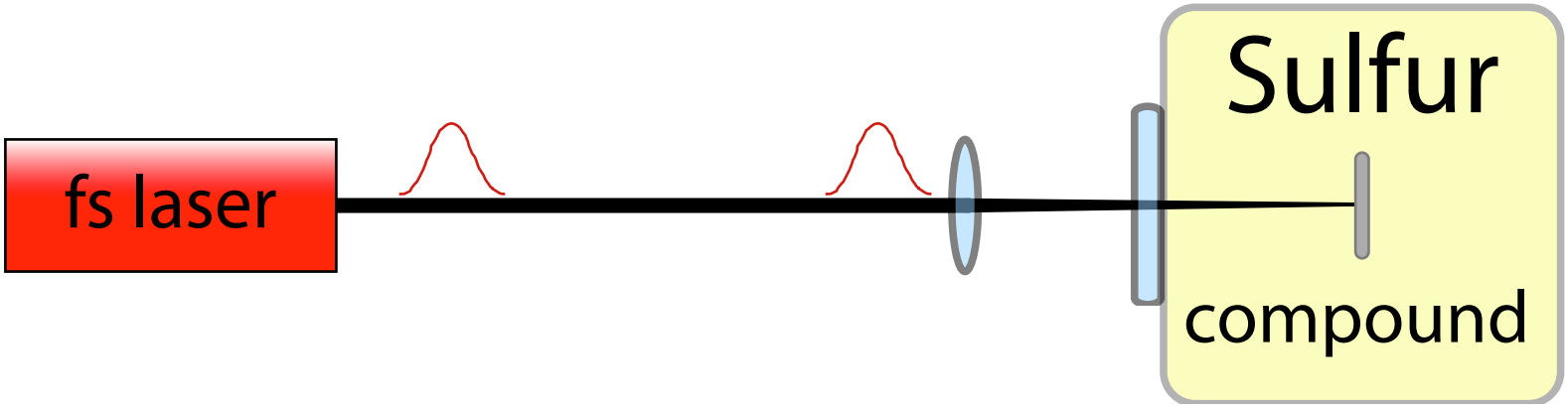
Understanding a material that extends silicon's reach:

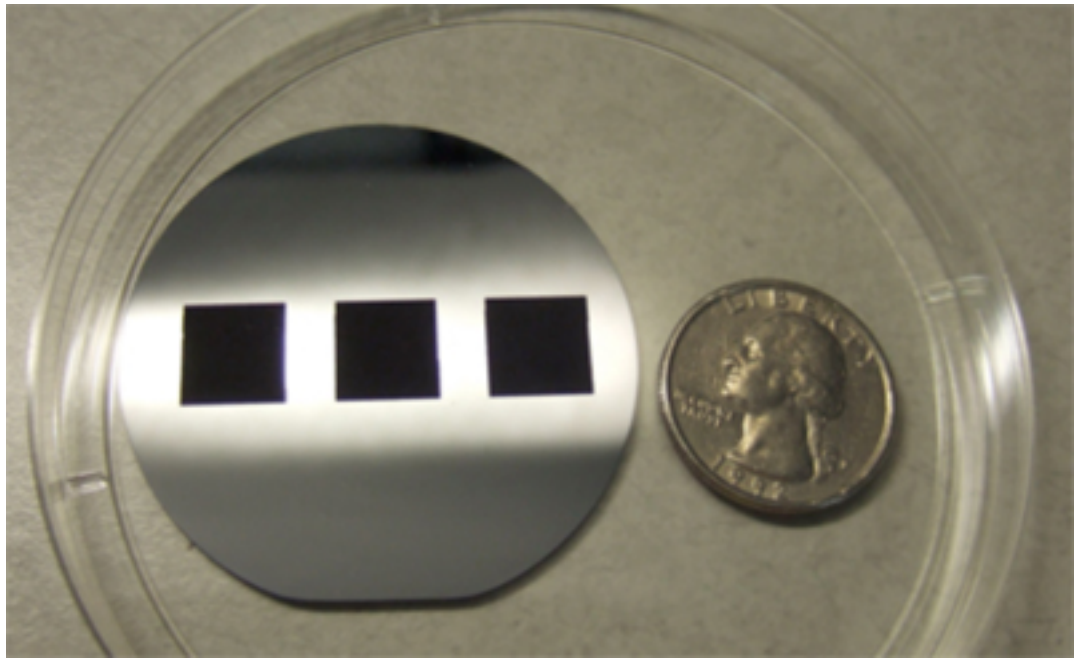
- What we know about laser doping of silicon
- Structural role of dopants in infrared absorptance

Understanding a material that extends silicon's reach:

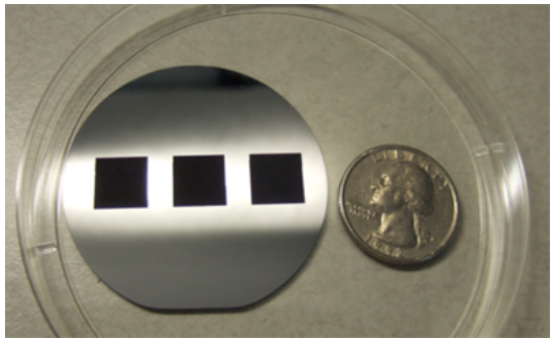
- What we know about laser doping of silicon
- Structural role of dopants in infrared absorptance
- New developments and directions

femtosecond laser doped silicon

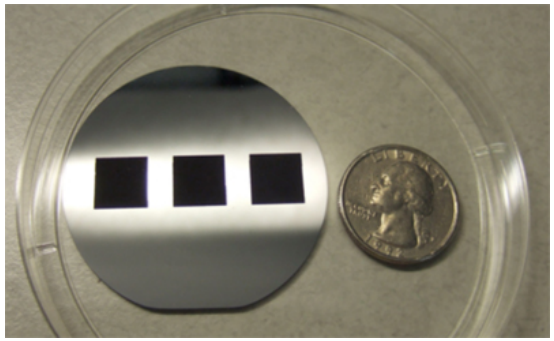


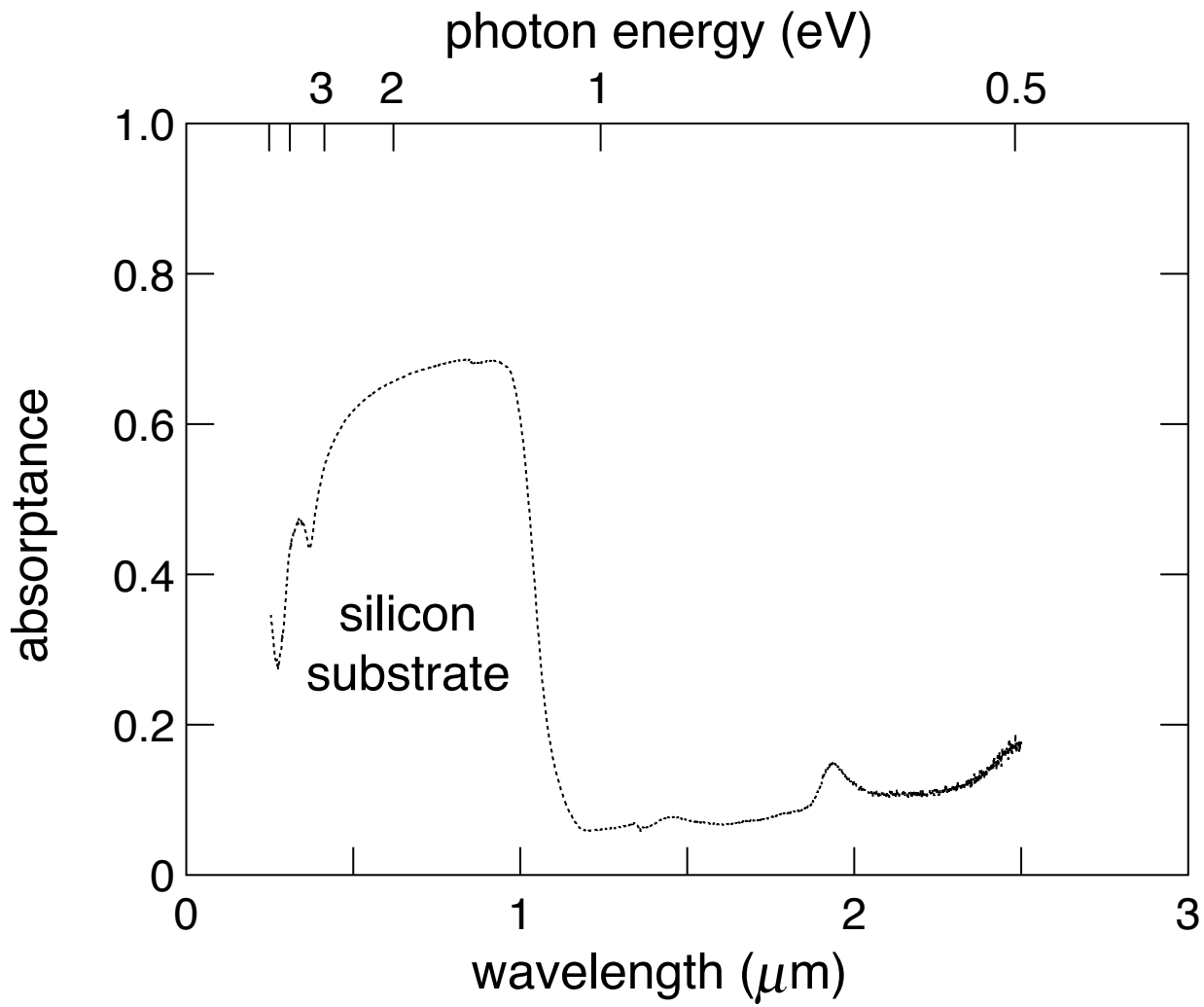


fs laser
Sulfur
compound

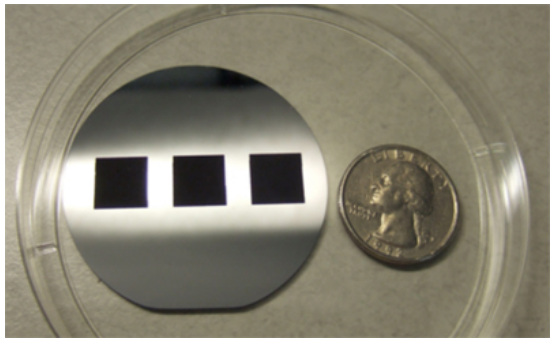


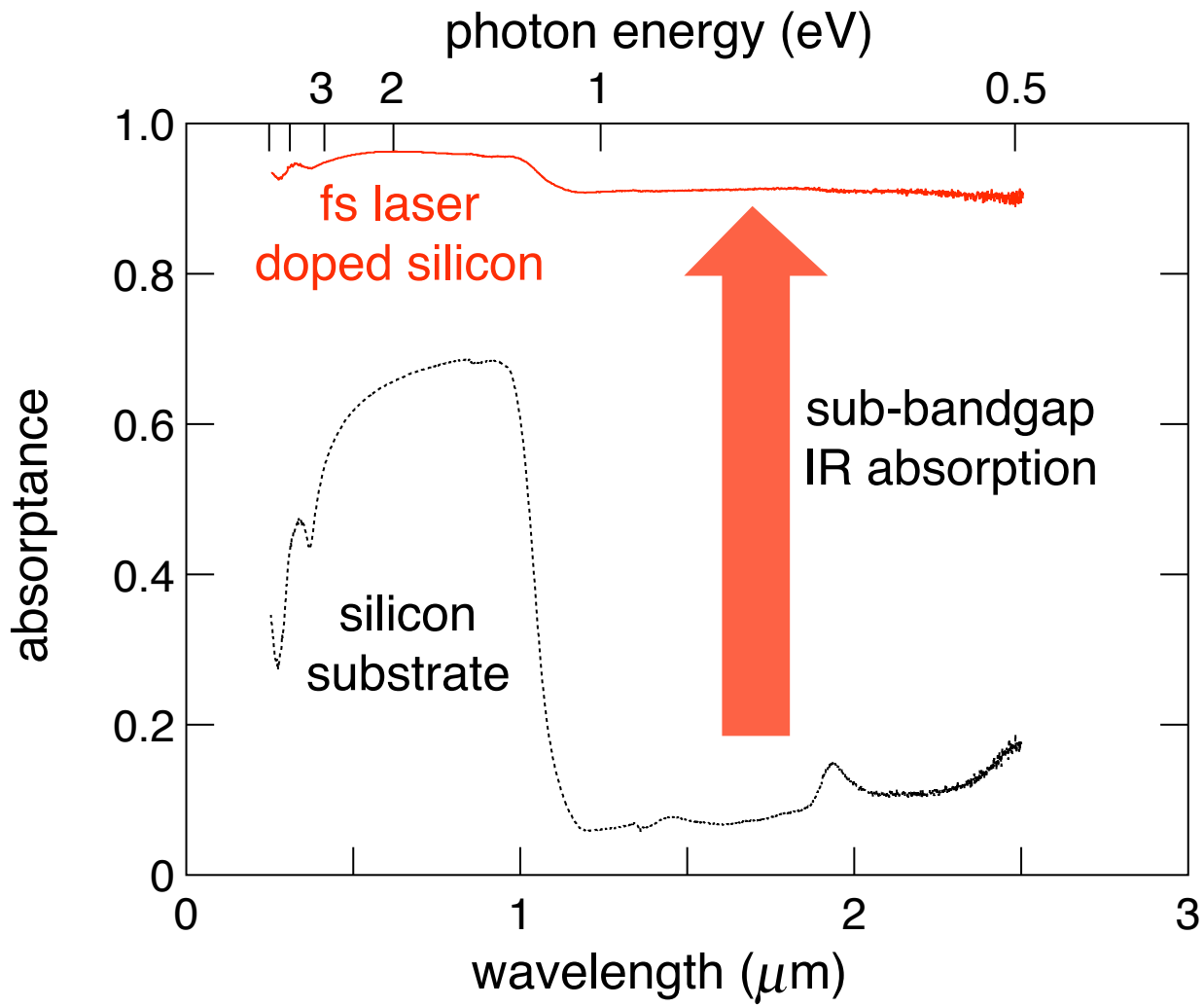
fs laser
Sulfur
compound



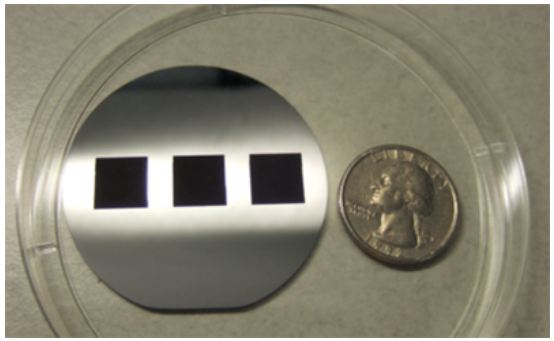

photon energy (eV)
3
2
1
0.5
1.0
0.8
0.6
0.4
0.2
0
absorptance
silicon
substrate
0
1
2
3
wavelength (μm)

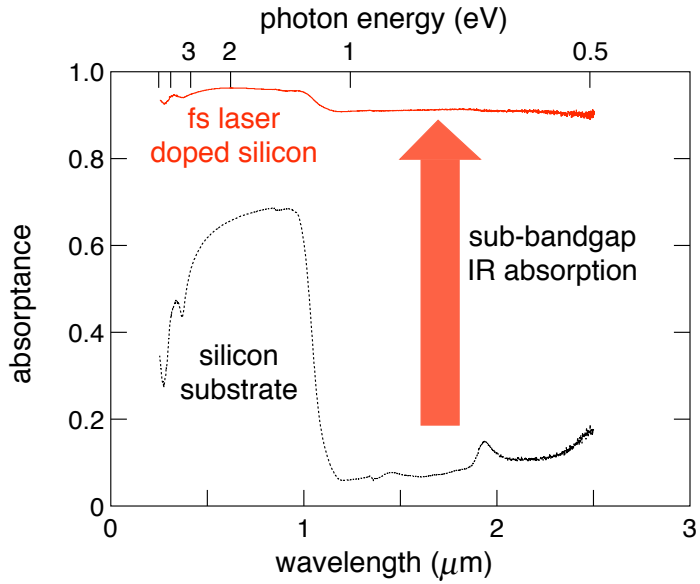
fs laser
Sulfur
compound



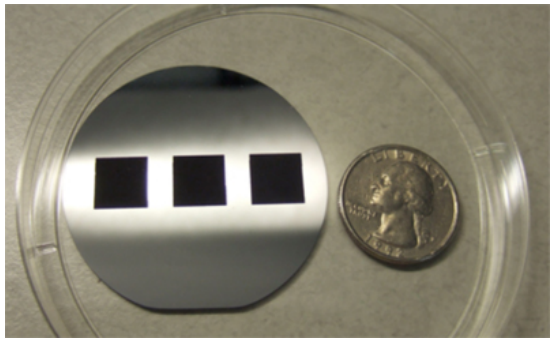

photon energy (eV)
3
2
1
0.5
1.0
0.8
0.6
0.4
0.2
0
absorptance
fs laser
doped silicon
sub-bandgap
IR absorption
silicon
substrate
0
1
2
3
wavelength (μm)

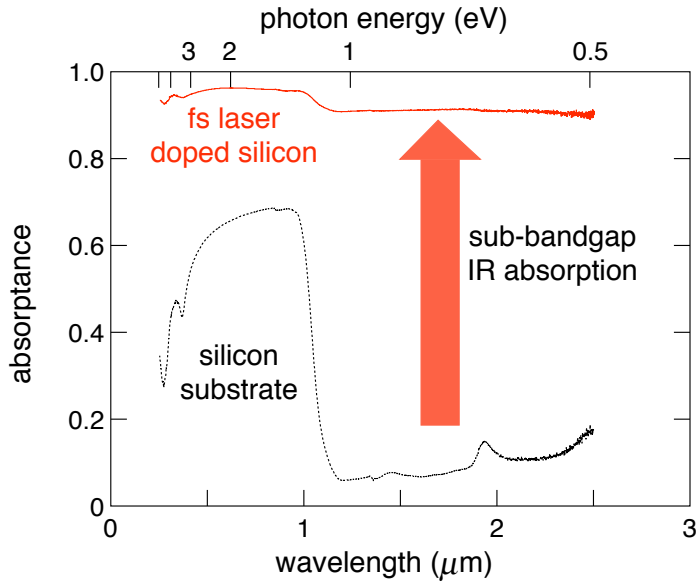
fs laser
Sulfur
compound

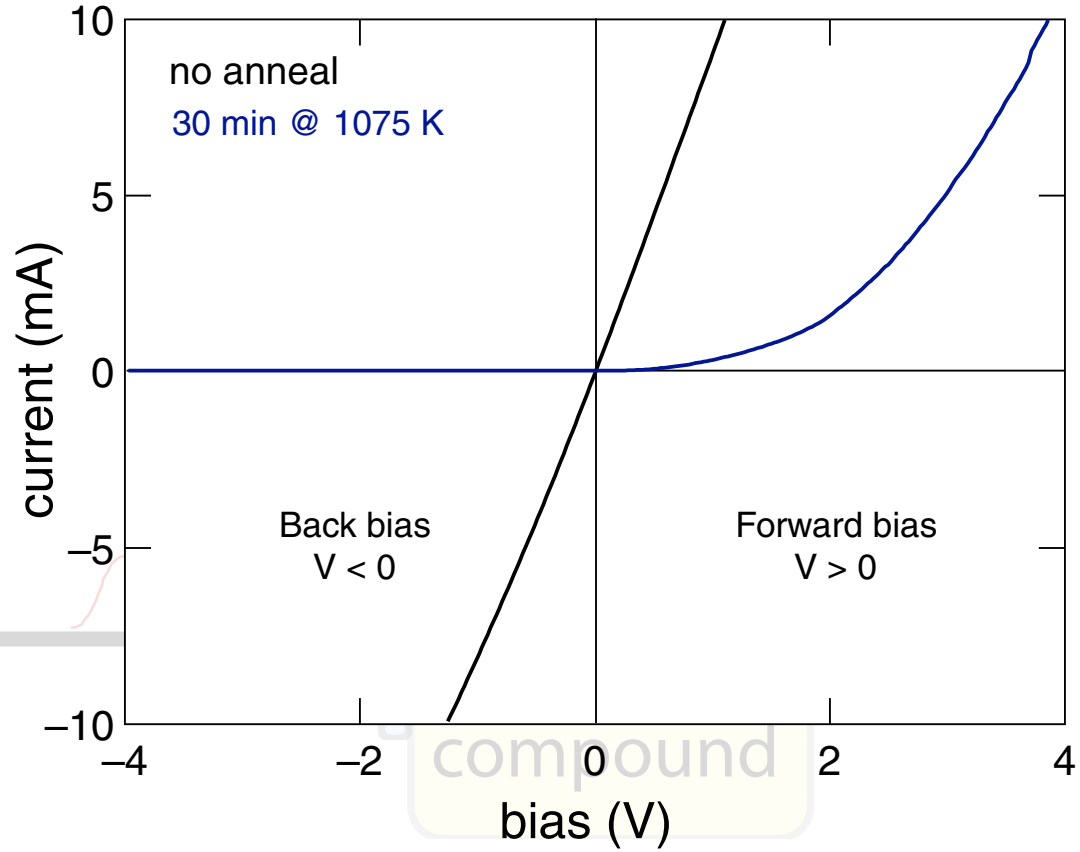



photon energy (eV)
3
2
1
0.5
1.0
0.8
0.6
0.4
0.2
0
absorptance
fs laser
doped silicon
sub-bandgap
IR absorption
silicon
substrate
0
1
2
3
wavelength (μm)

fs laser
Sulfur
compound

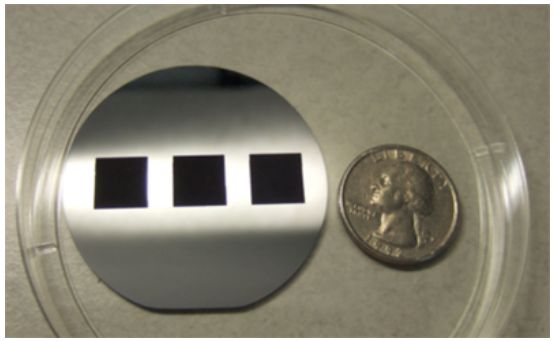


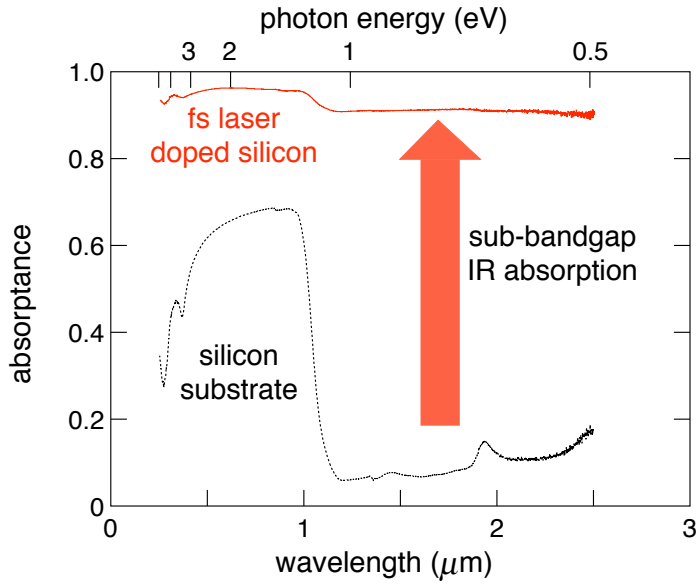


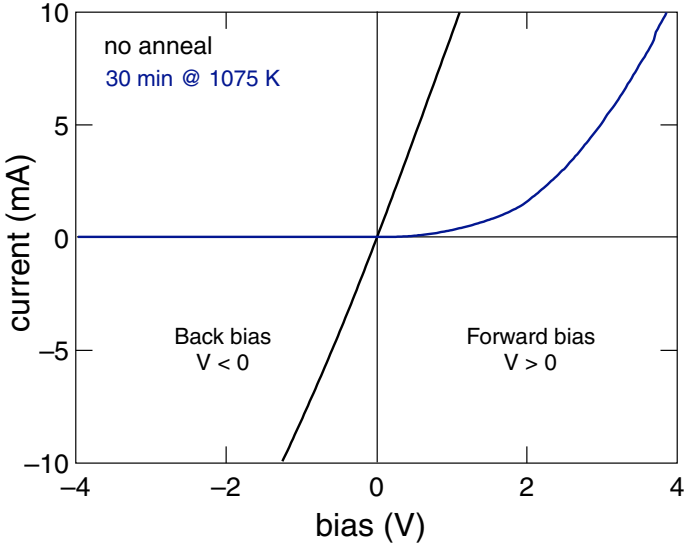


fs laser

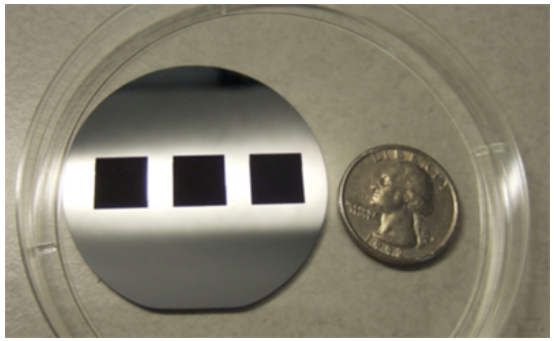
compound

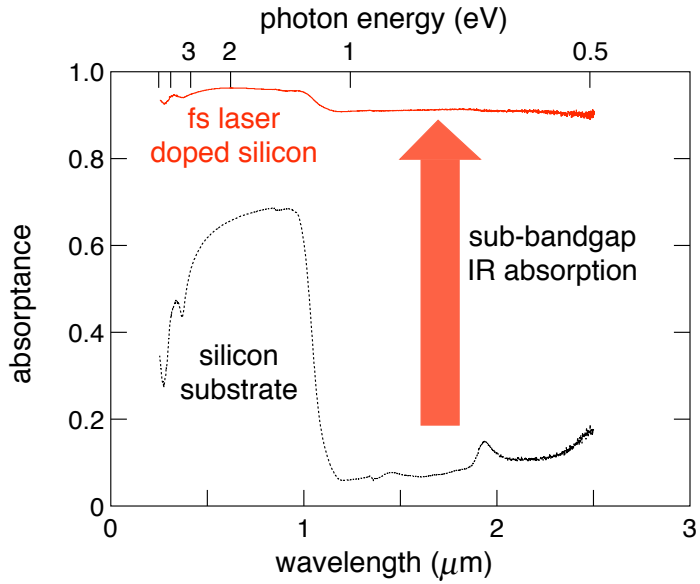


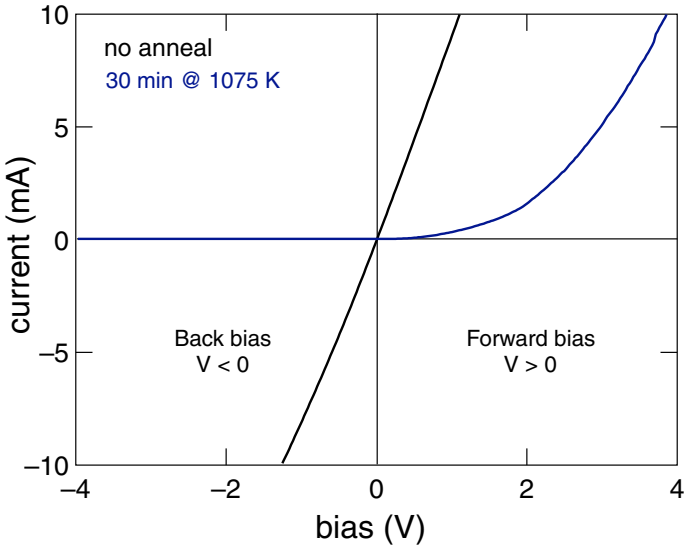

photon energy (eV)
3
2
1
0.5
1.0
0.8
0.6
0.4
0.2
0
absorptance
fs laser
doped silicon
sub-bandgap
IR absorption
silicon
substrate
0
1
2
3
wavelength (μm)

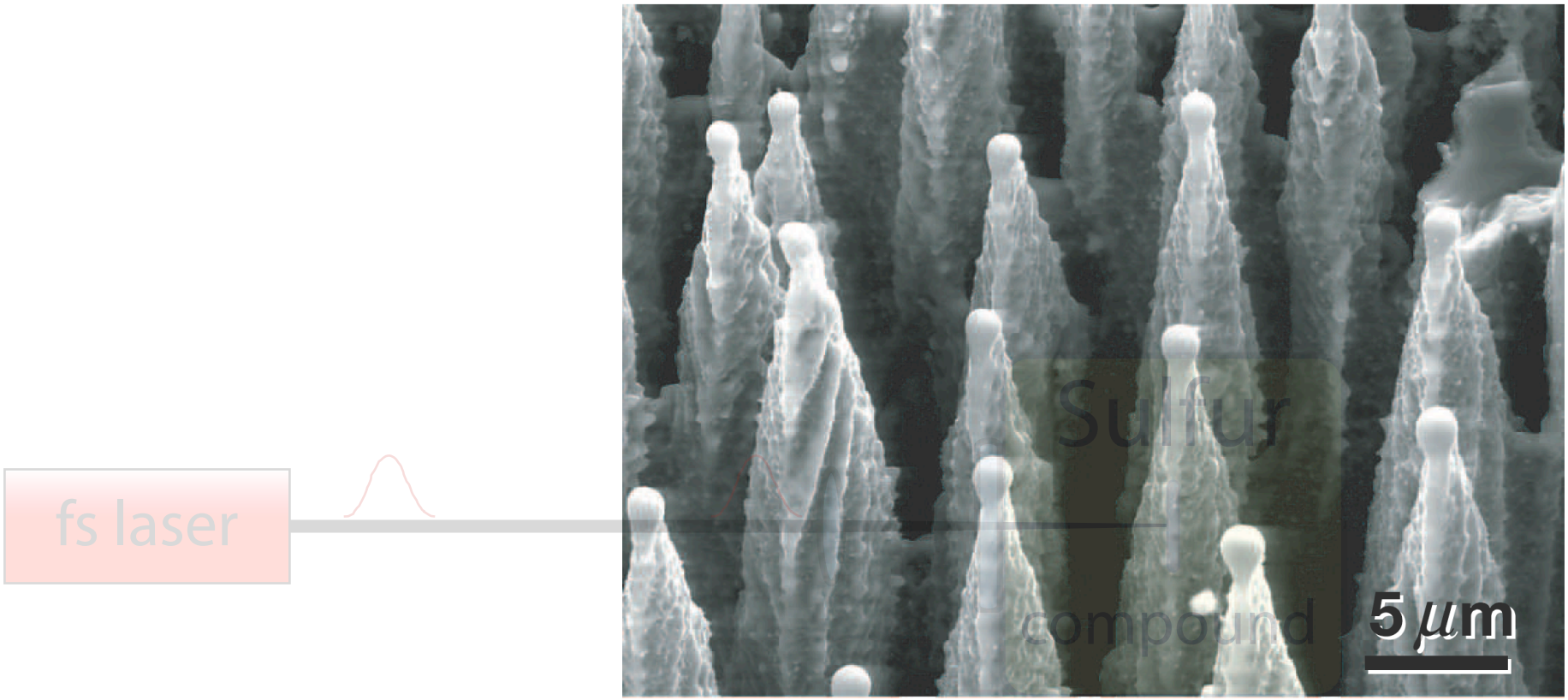

10
5
0
−5
−10
current (mA)
no anneal
30 min @ 1075 K
Back bias
V < 0
Forward bias
V > 0
−4
−2
0
2
4
bias (V)

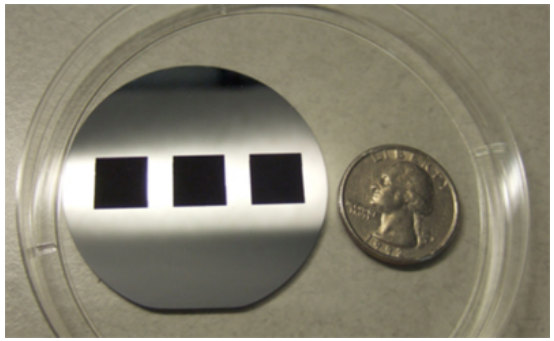
fs laser
Sulfur
compound

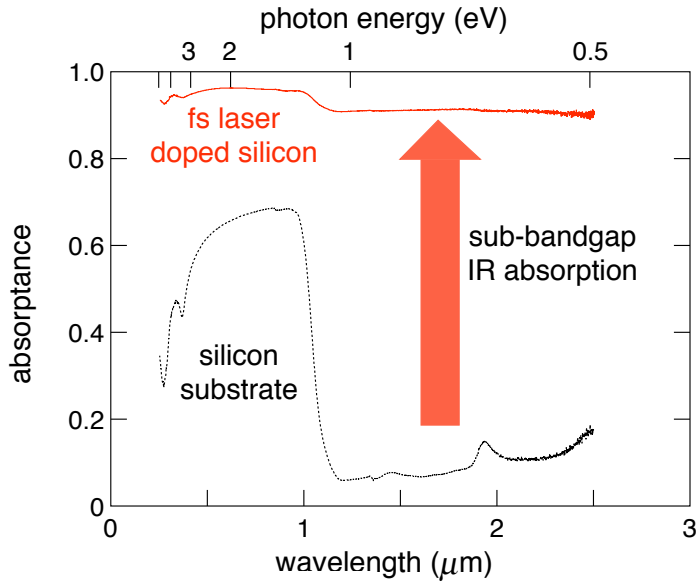


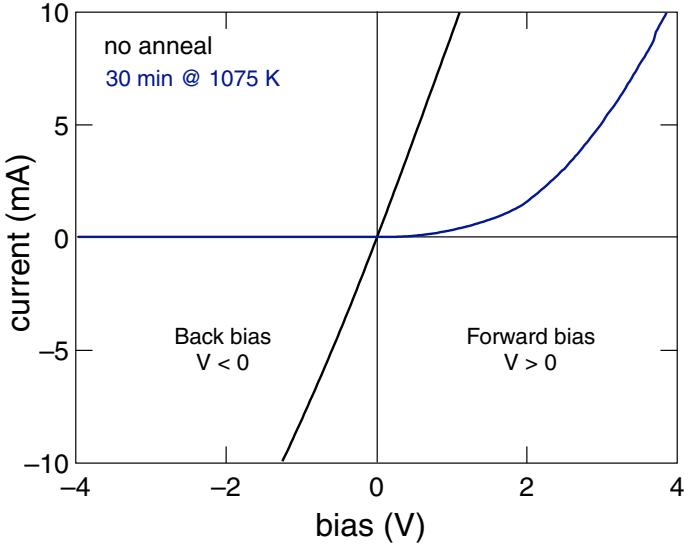

photon energy (eV)
3
2
1
0.5
1.0
0.8
0.6
0.4
0.2
0
absorptance
fs laser
doped silicon
sub-bandgap
IR absorption
silicon
substrate
0
1
2
3
wavelength (μm)


10
5
0
−5
−10
current (mA)
no anneal
30 min @ 1075 K
Back bias
V < 0
Forward bias
V > 0
−4
−2
0
2
4
bias (V)


fs laser
Sulfur
compound
5 μm




photon energy (eV)
3
2
1
0.5
1.0
0.8
0.6
0.4
0.2
0
absorptance
fs laser
doped silicon
sub-bandgap
IR absorption
silicon
substrate
0
1
2
3
wavelength (μm)


10
5
0
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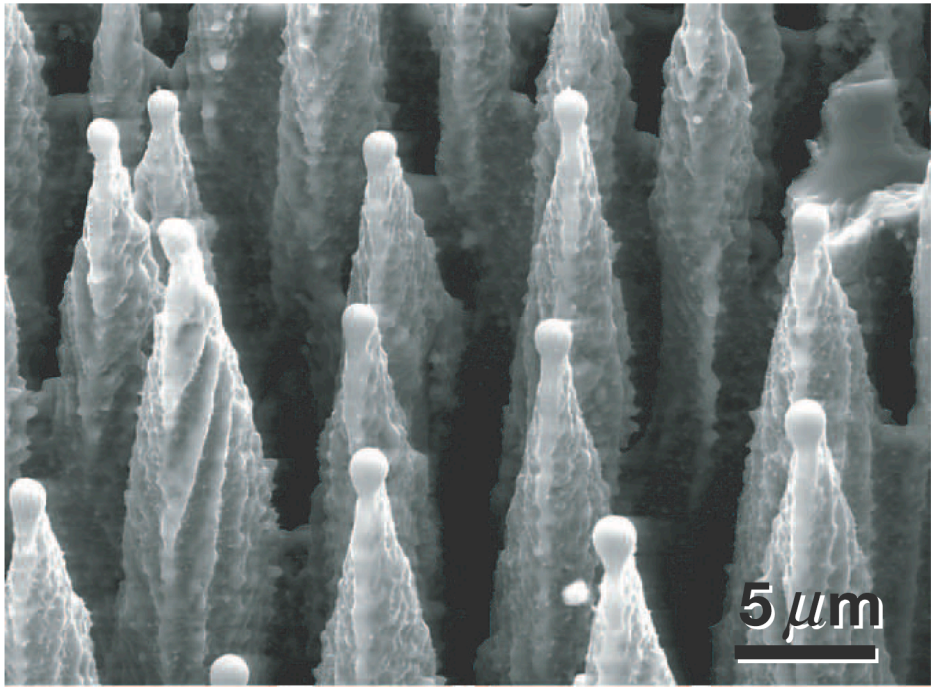
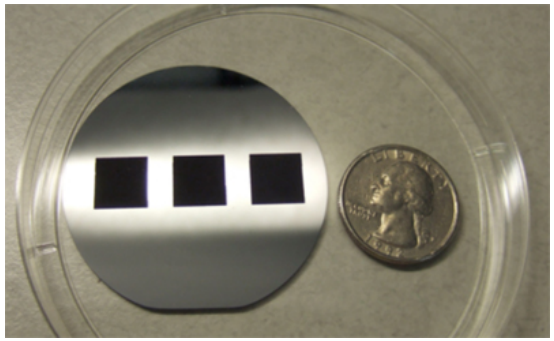
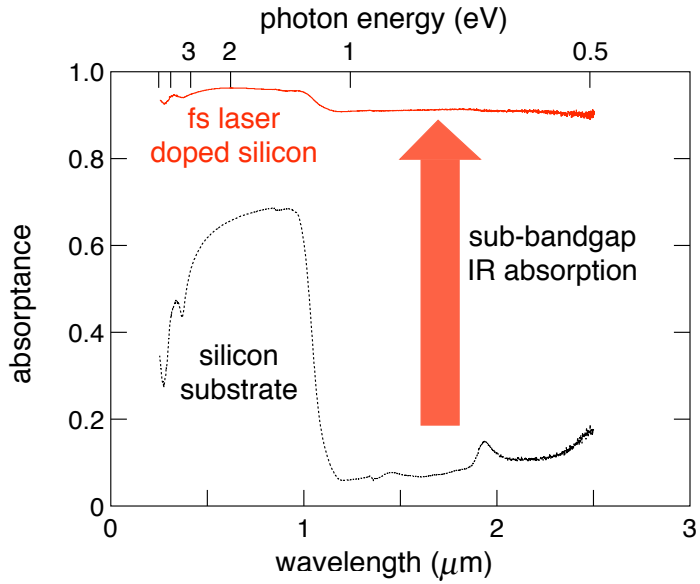
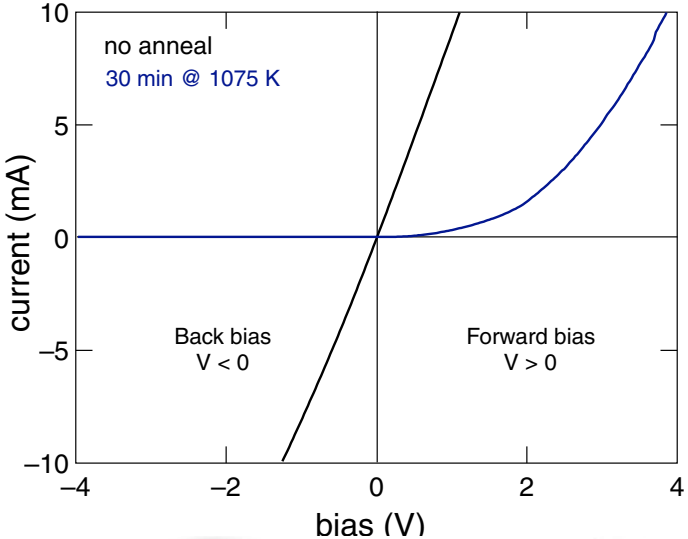
no anneal
30 min @ 1075 K
Back bias
V < 0
Forward bias
V > 0
−4
−2
0
2
4
bias (V)

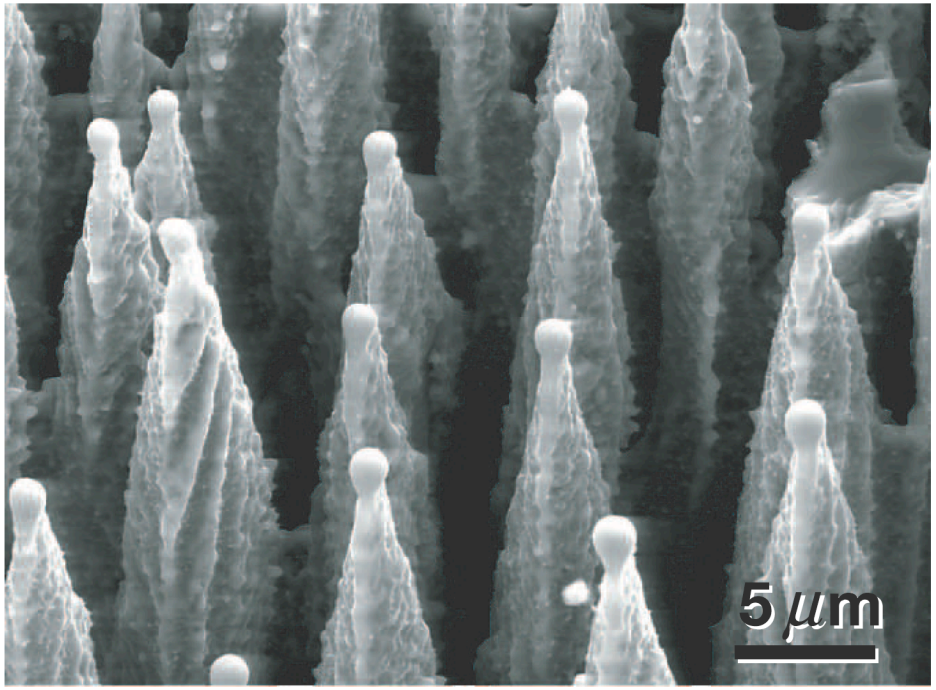

5 μm

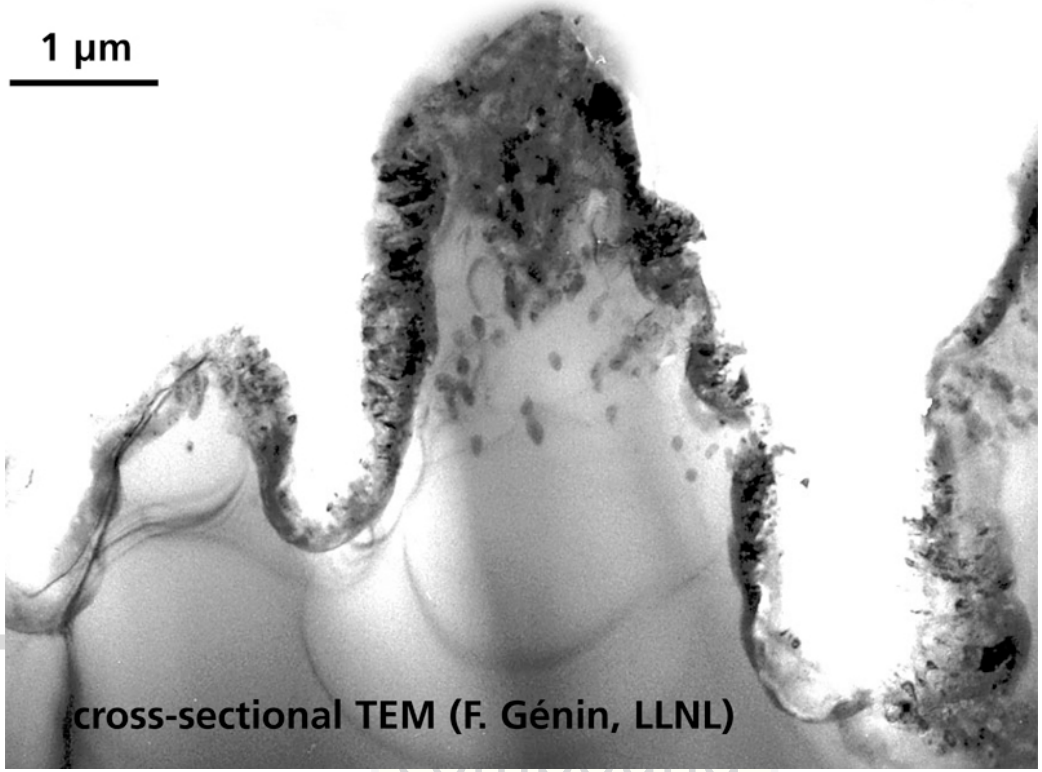
Sulfur
compound

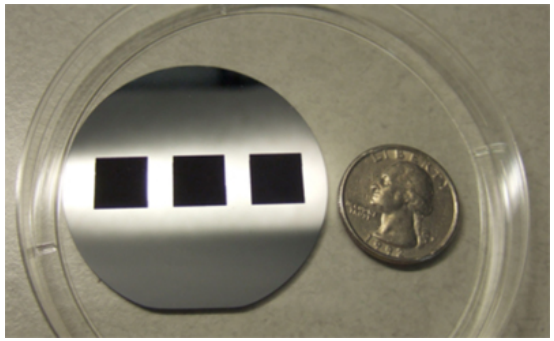


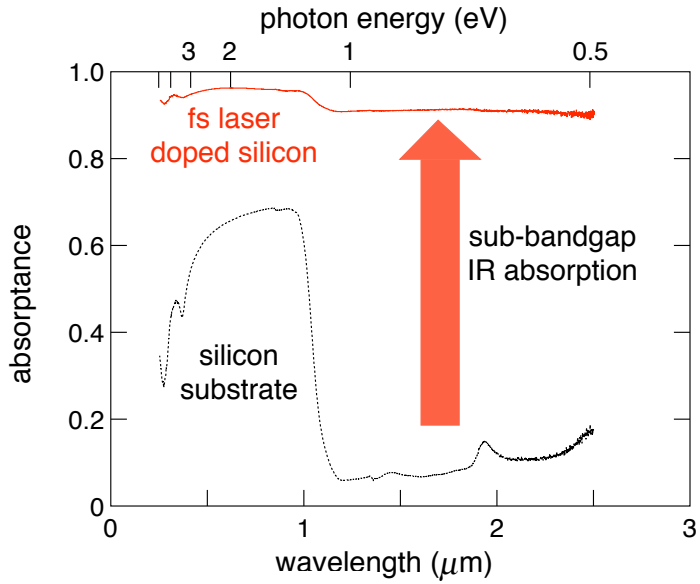

photon energy (eV)
3
2
1
0.5
1.0
0.8
0.6
0.4
0.2
0
absorptance
fs laser
doped silicon
sub-bandgap
IR absorption
silicon
substrate
0
1
2
3
wavelength (μm)

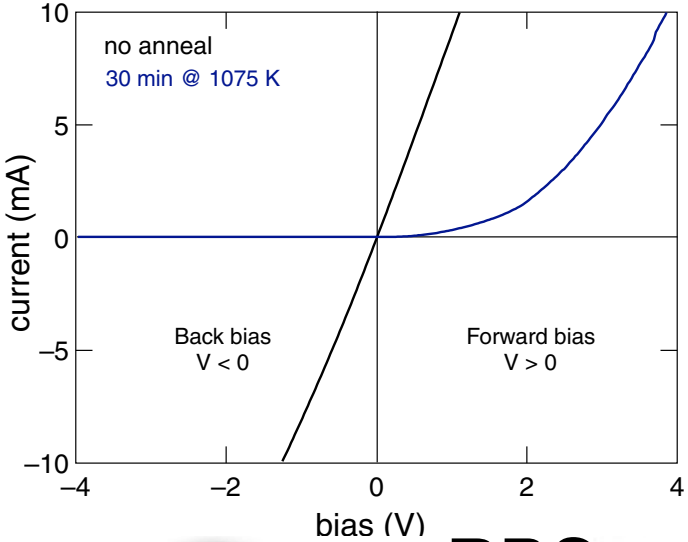

10
5
0
−5
−10
current (mA)
no anneal
30 min @ 1075 K
Back bias
V < 0
Forward bias
V > 0
−4
−2
0
2
4
bias (V)

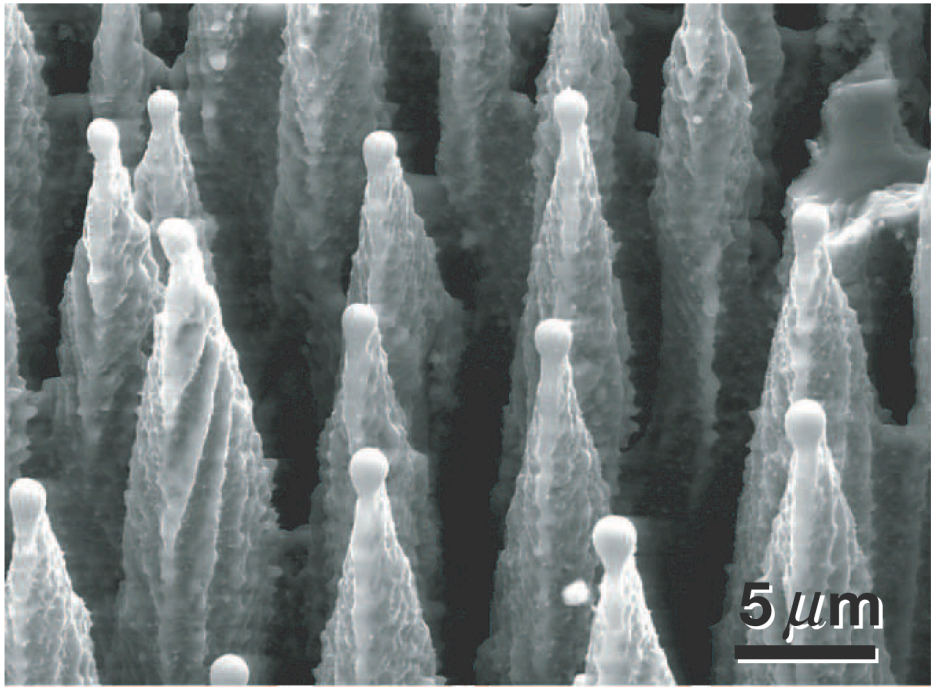

5 μm

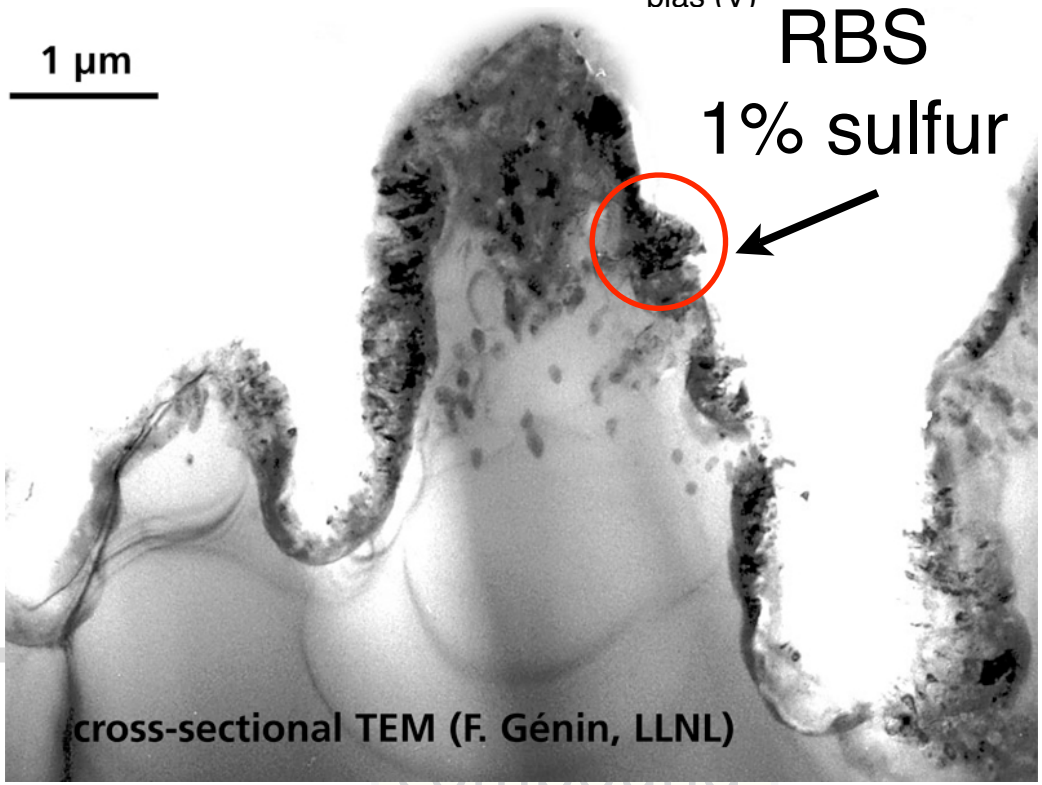

1 μm
cross-sectional TEM (F. Génin, LLNL)

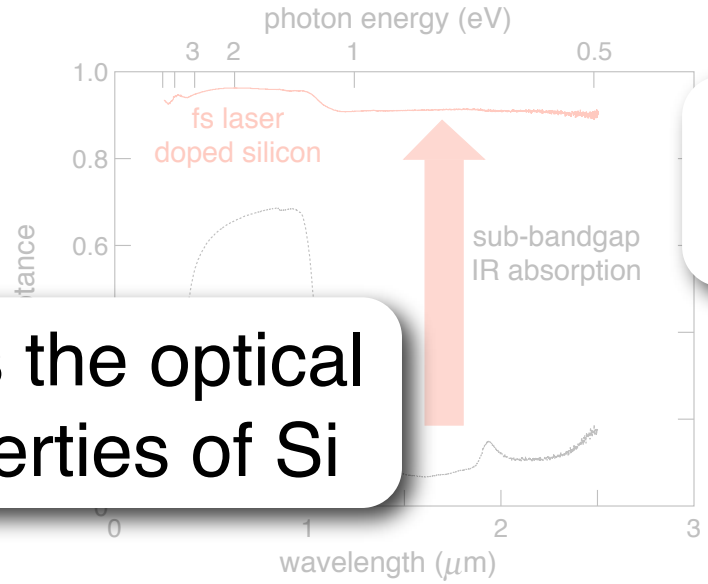



photon energy (eV)
3
2
1
0.5
1.0
0.8
0.6
0.4
0.2
0
absorptance
fs laser
doped silicon
sub-bandgap
IR absorption
silicon
substrate
0
1
2
3
wavelength (μm)

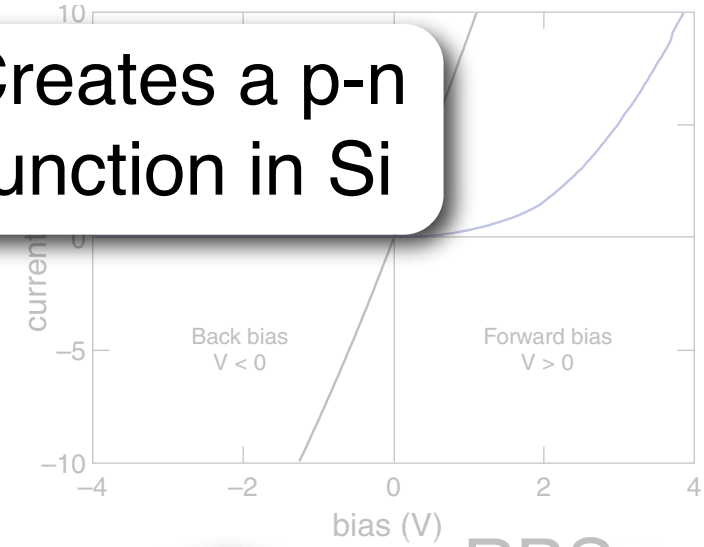

10
5
0
−5
−10
current (mA)
no anneal
30 min @ 1075 K
Back bias
V < 0
Forward bias
V > 0
−4
−2
0
2
4
bias (V)


5 μm

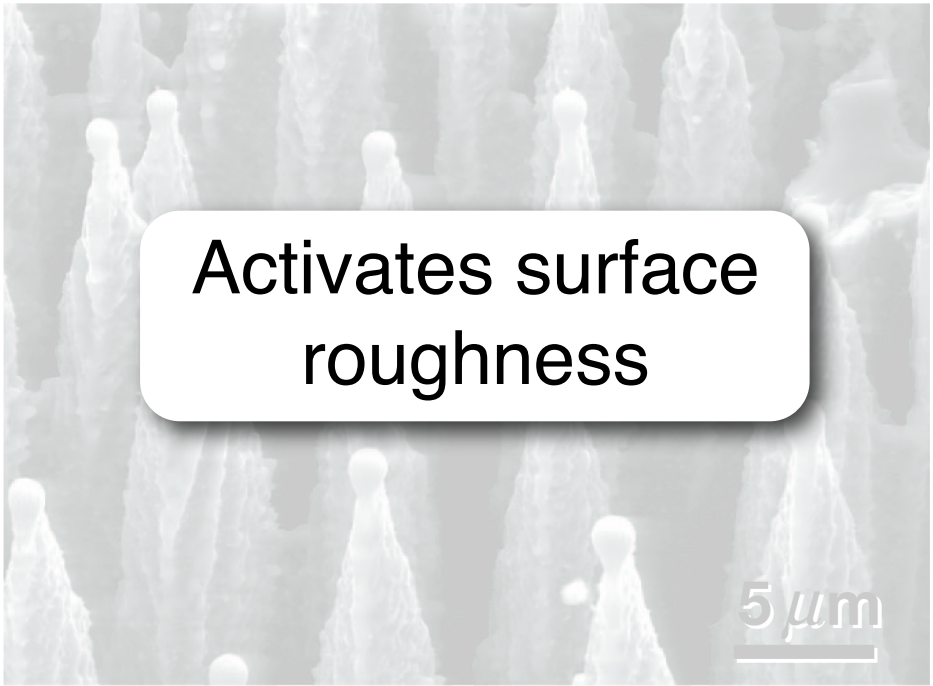

1 μm
RBS
1% sulfur
cross-sectional TEM (F. Génin, LLNL)



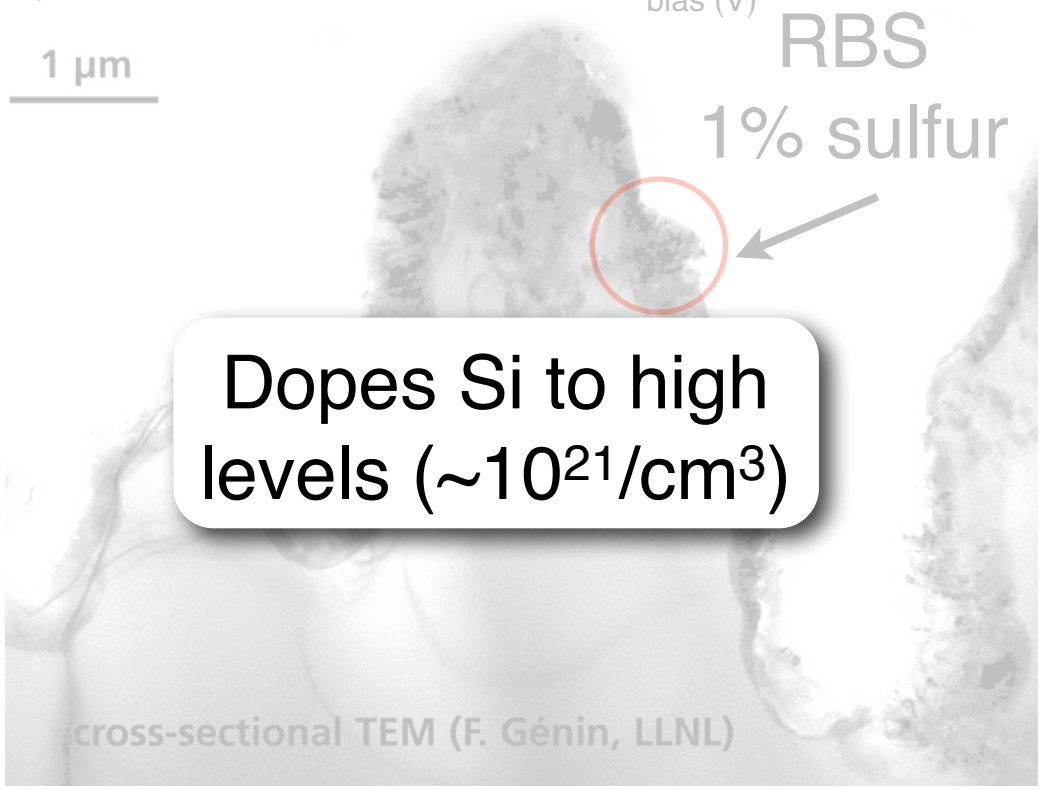
Alters the optical properties of Si



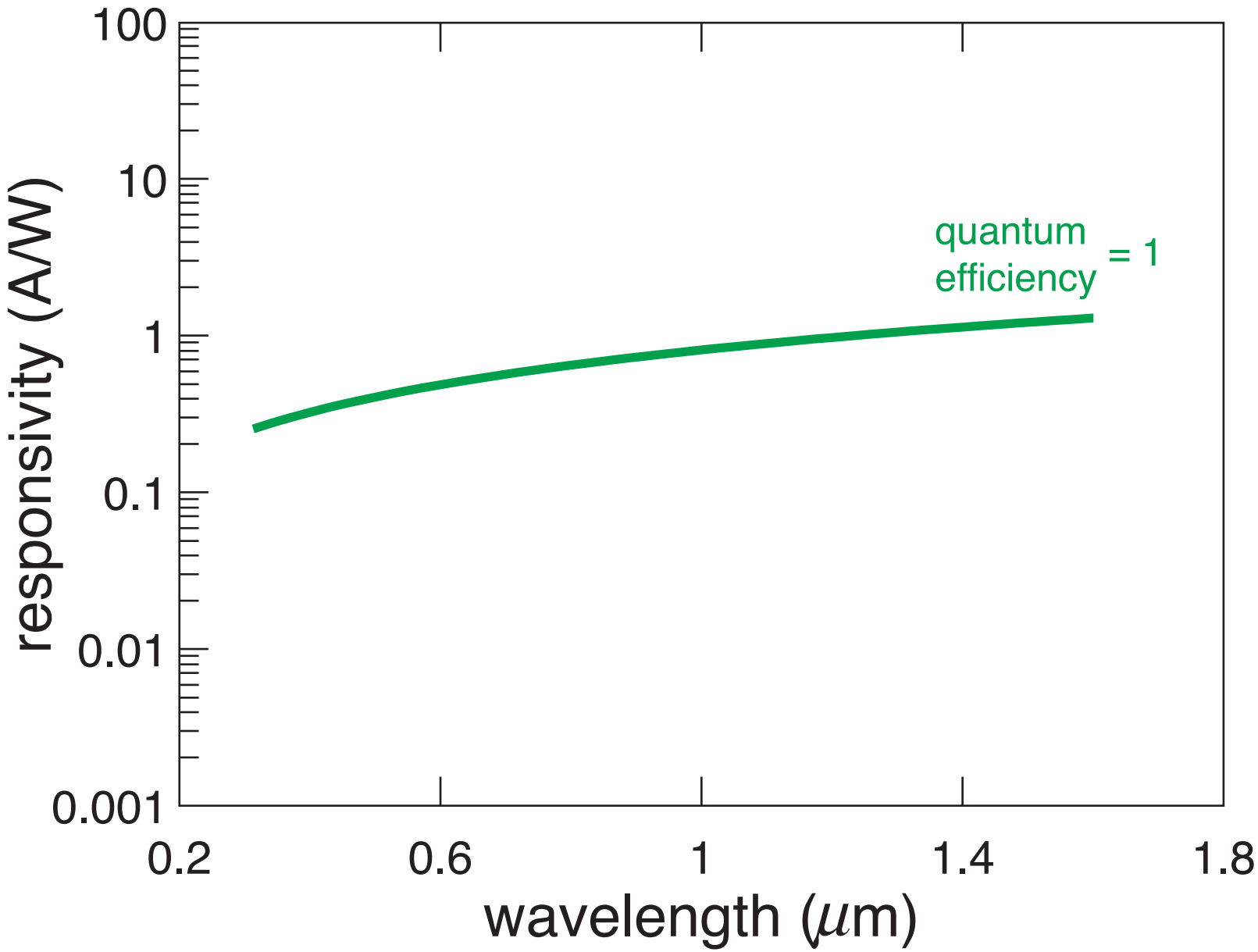
Creates a p-n junction in Si

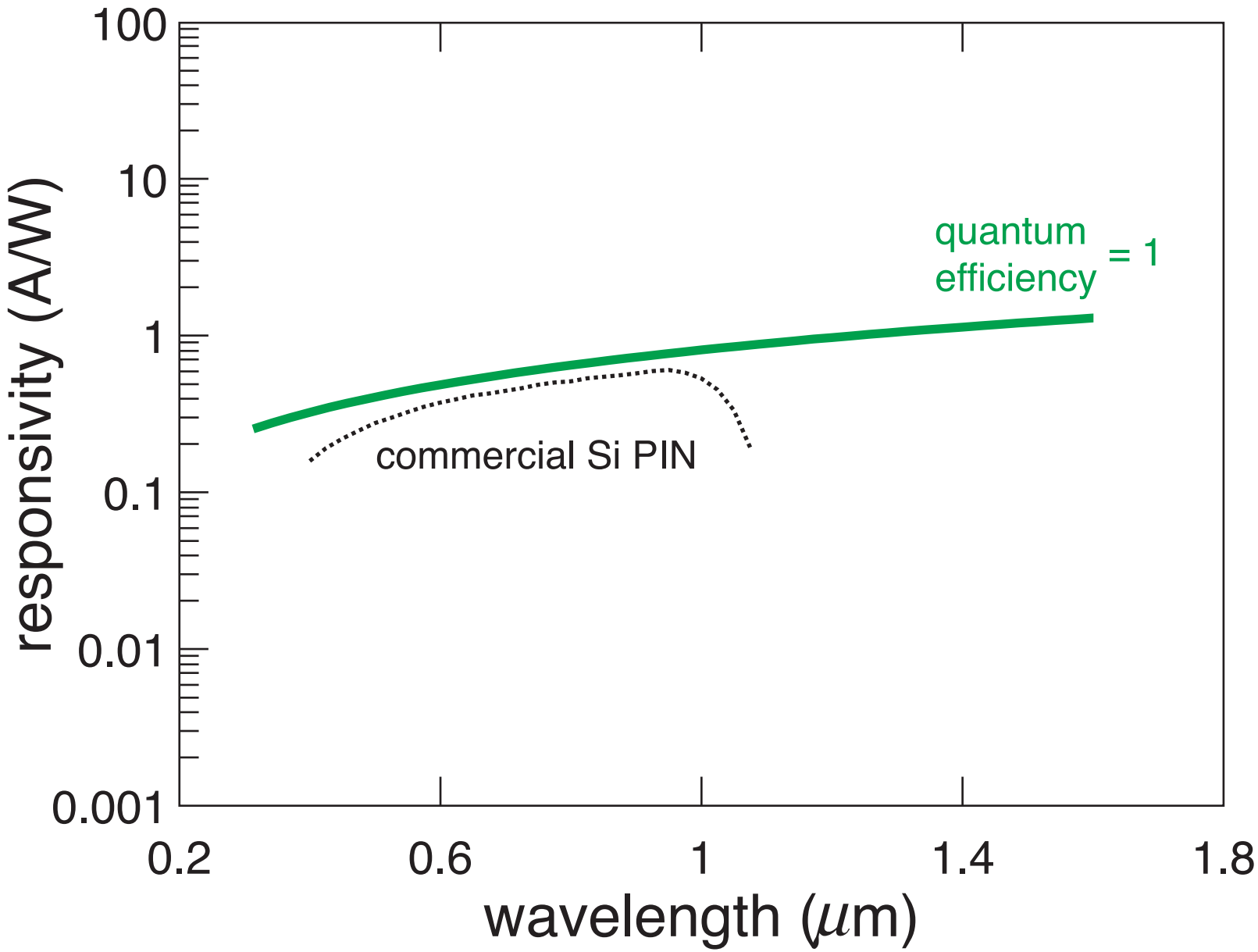


Activates surface roughness

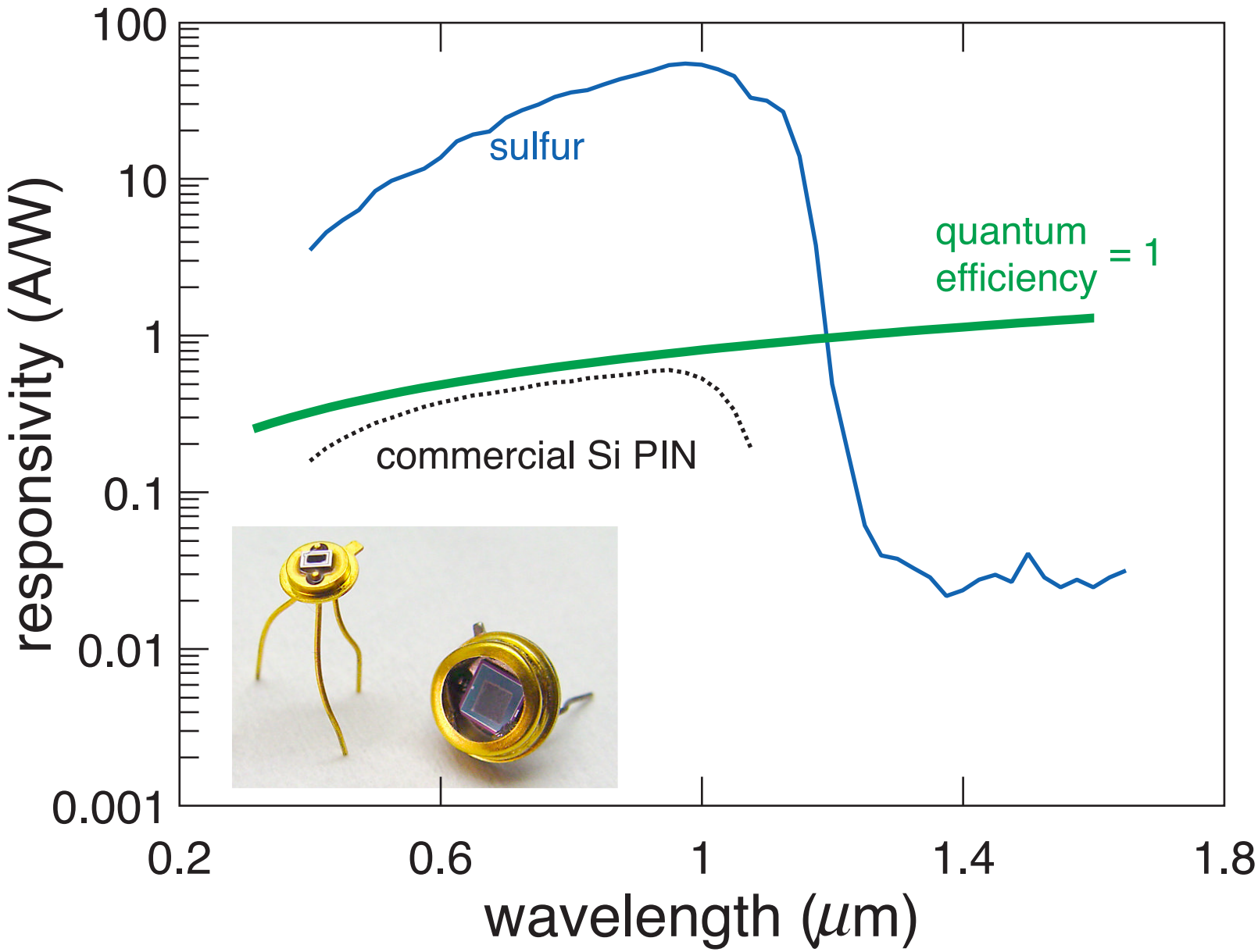


Dopes Si to high levels (~$10^{21}/cm^3$)

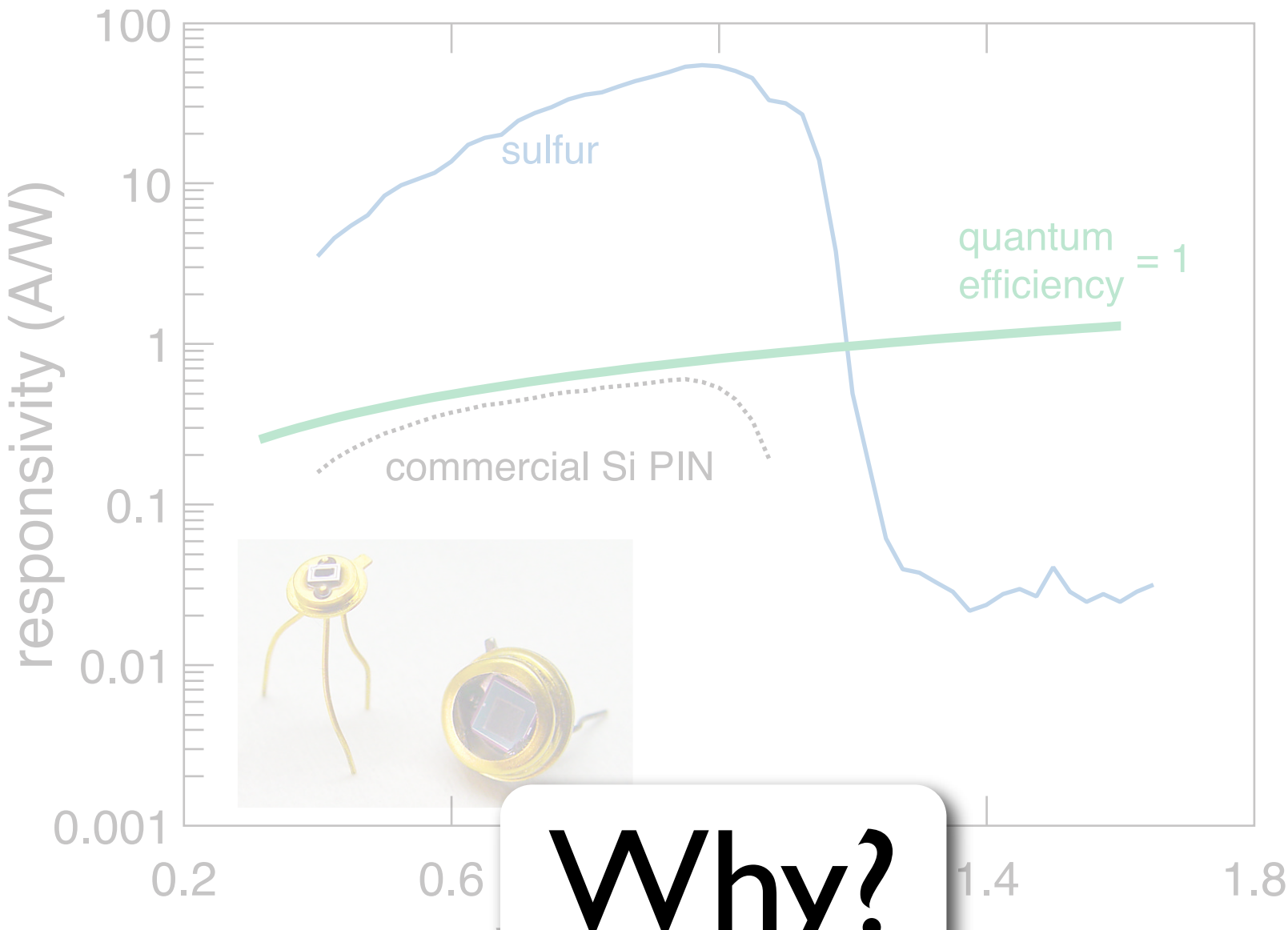

100
10
1
0.1
0.01
0.001
responsivity (A/W)
quantum
efficiency
= 1
0.2
0.6
1
1.4
1.8
wavelength (μm)


100
10
1
0.1
0.01
0.001
responsivity (A/W)
quantum
efficiency
= 1
commercial Si PIN
0.2
0.6
1
1.4
1.8
wavelength (μm)

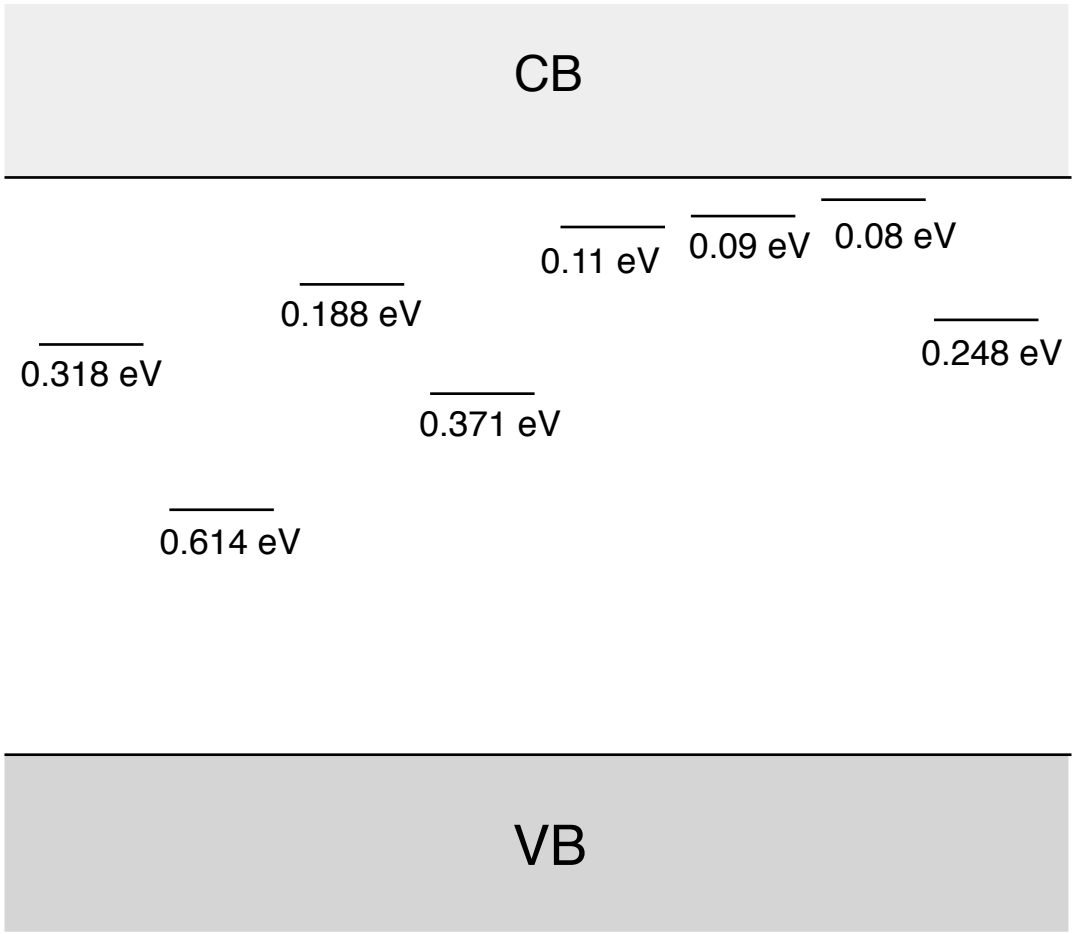
Laser-doping extends silicon's reach



Laser-doping extends silicon's reach

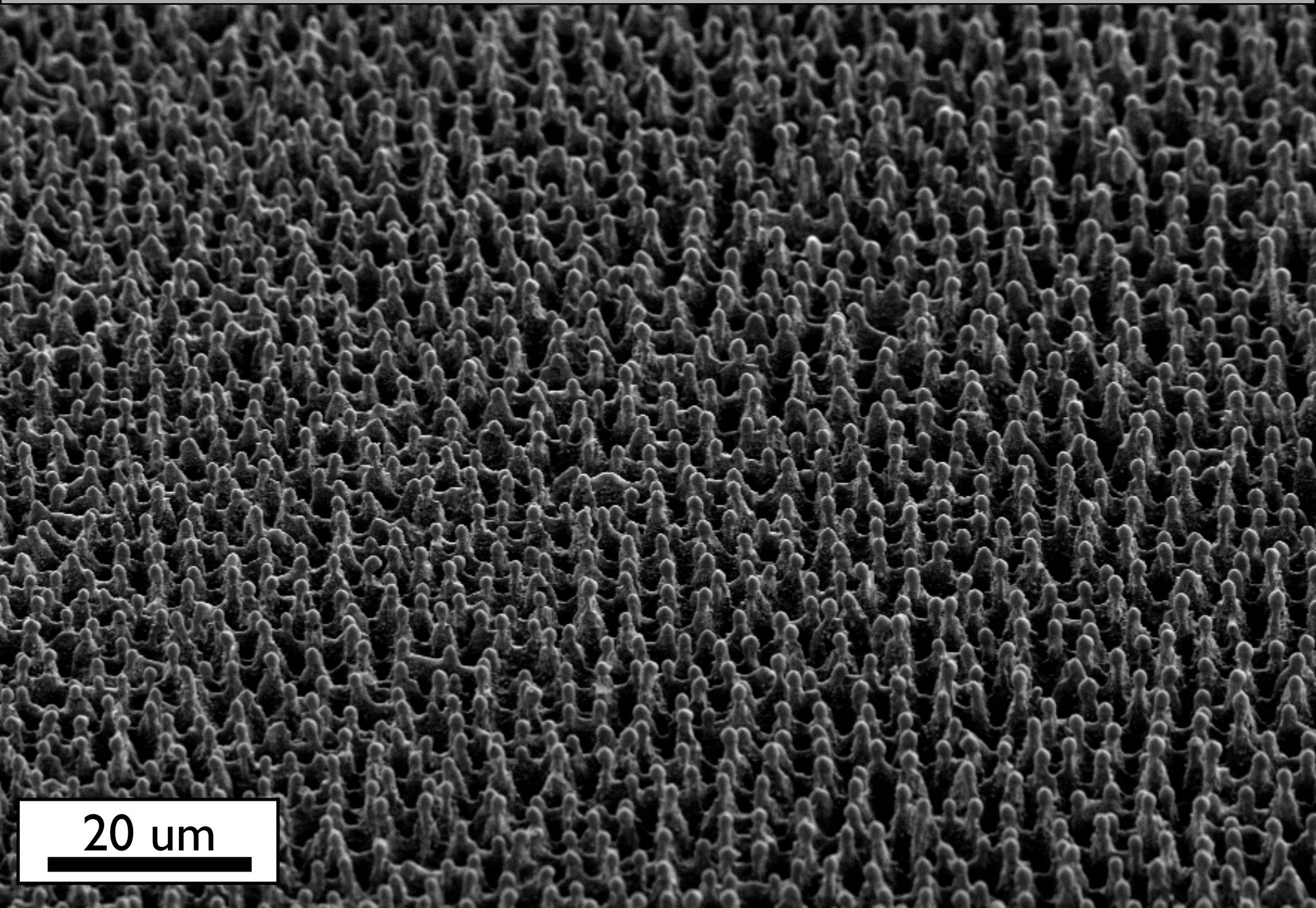


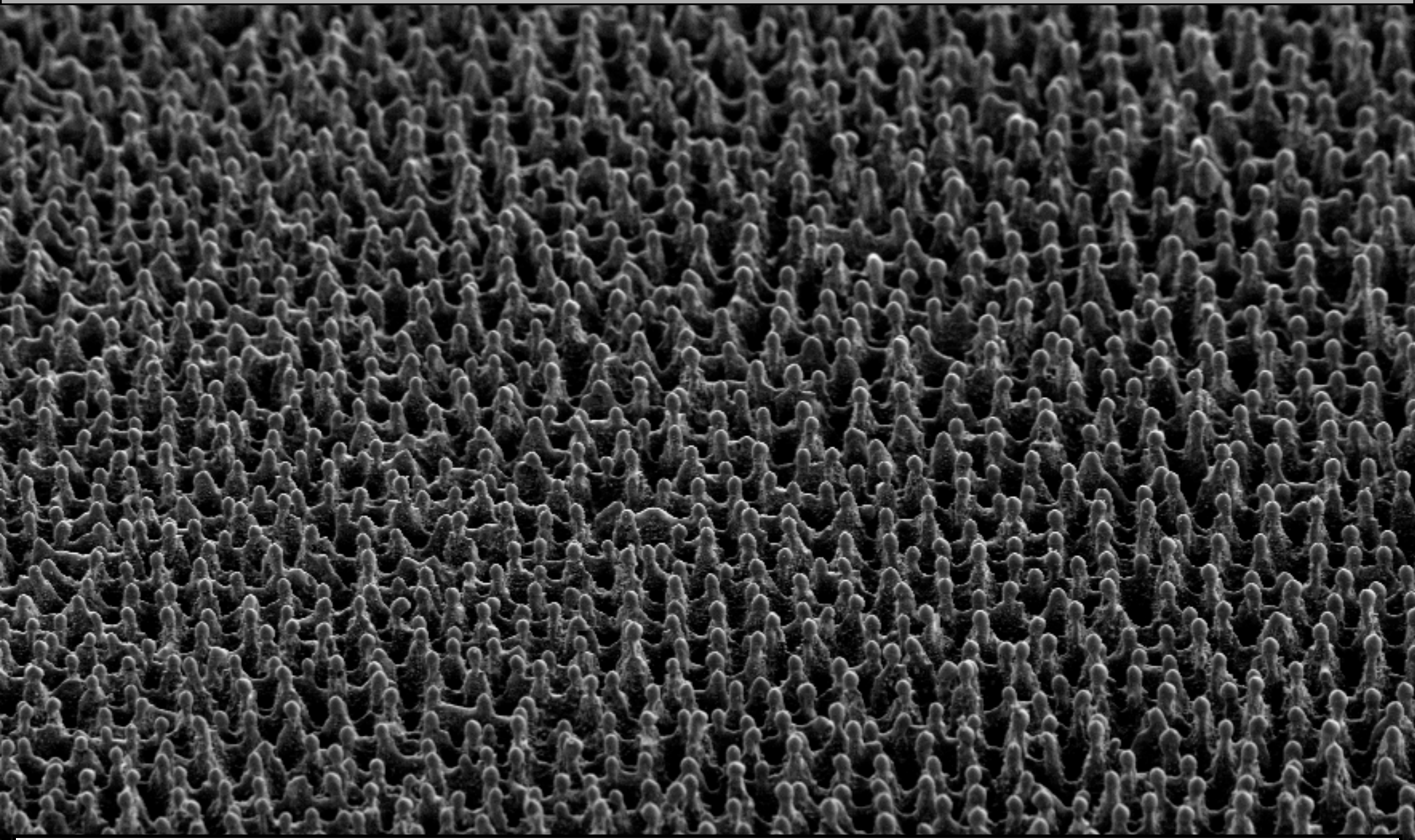
Why?



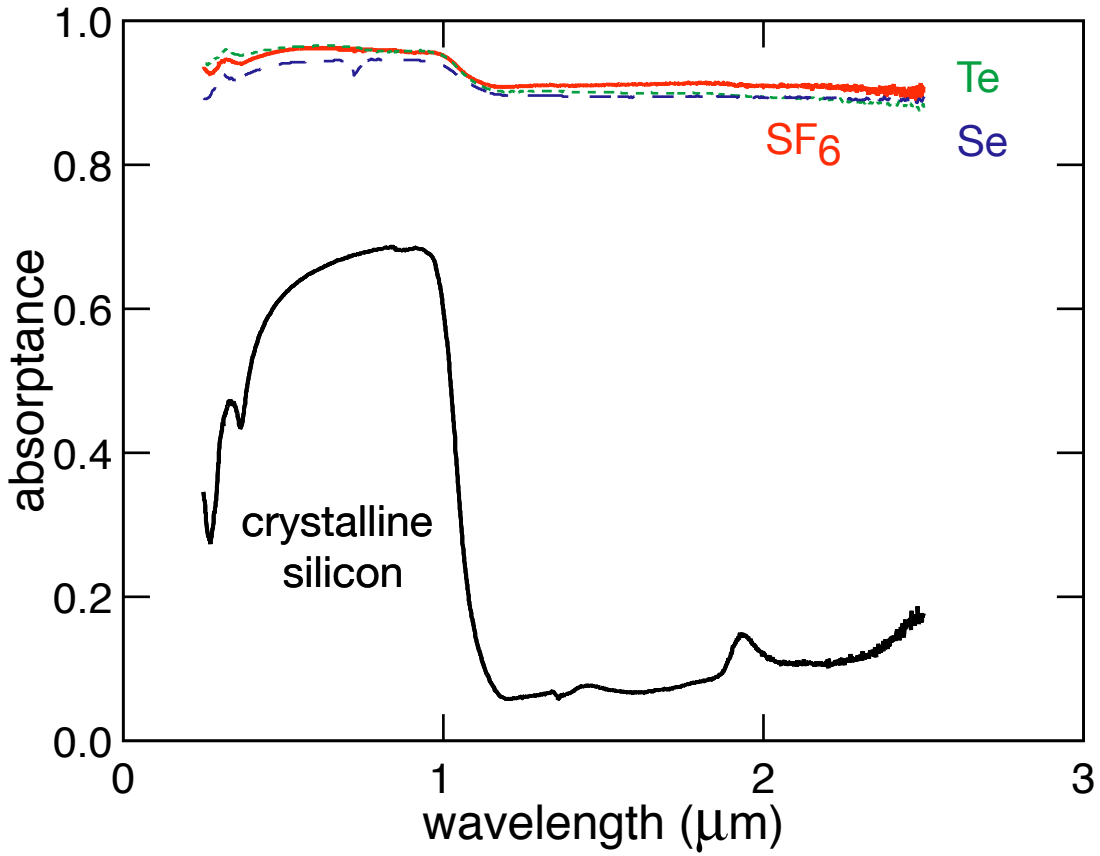
Janzén et al. , Phys. Rev. B 29, 1907 (1984)

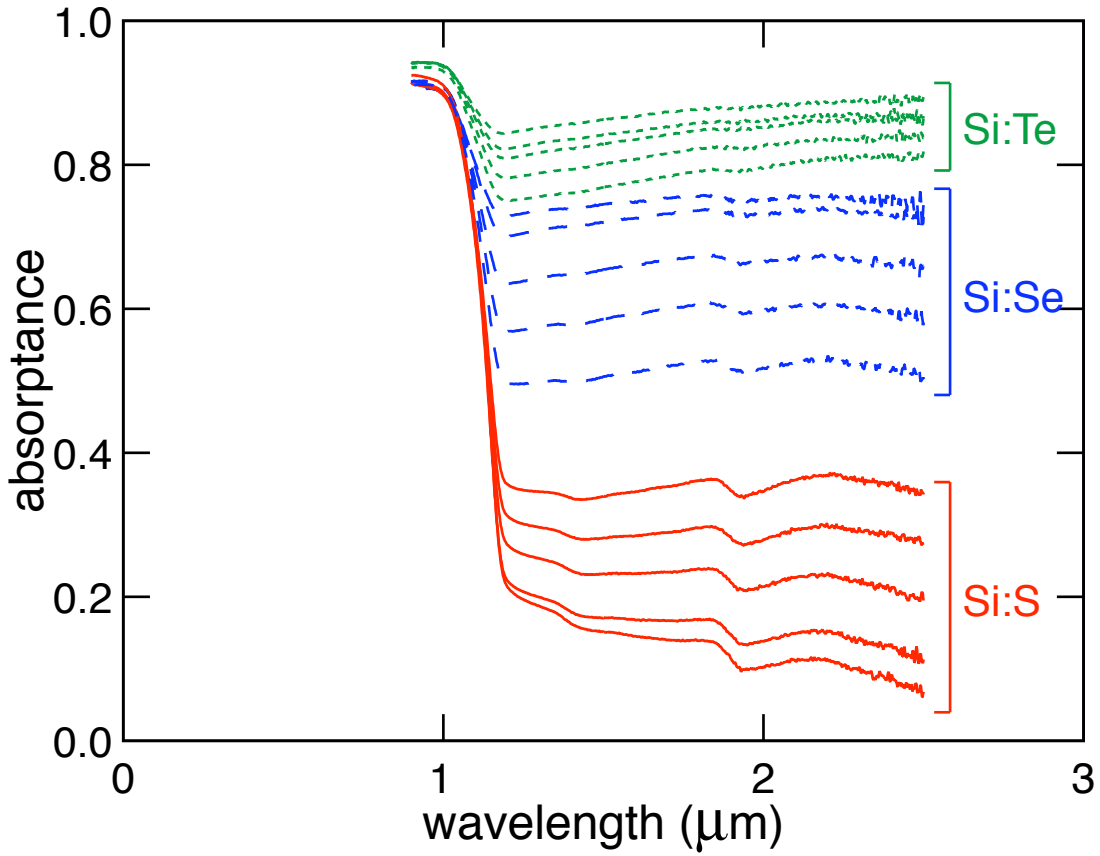
Hypothesis: non-equilibrium doping yields impurity band

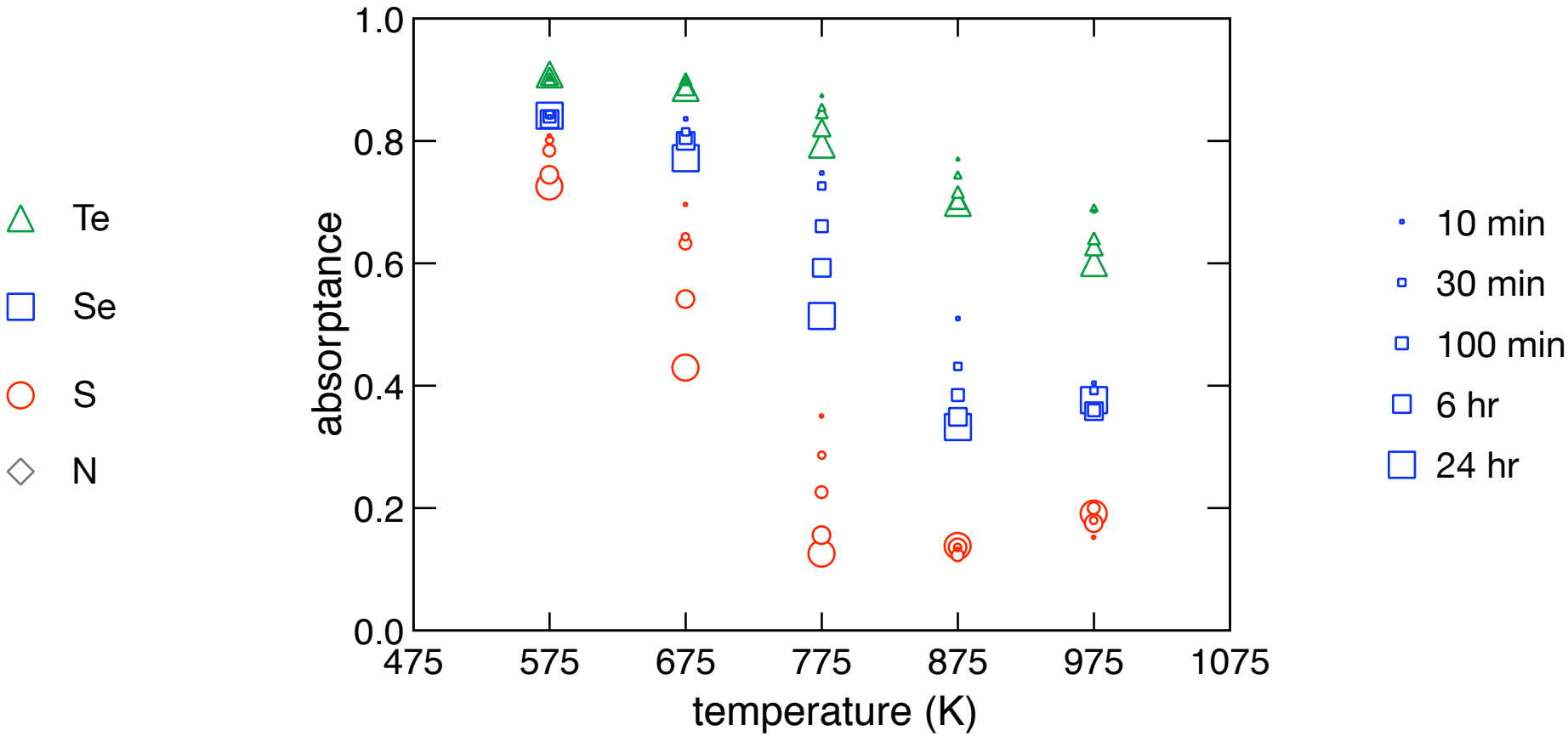

20 um



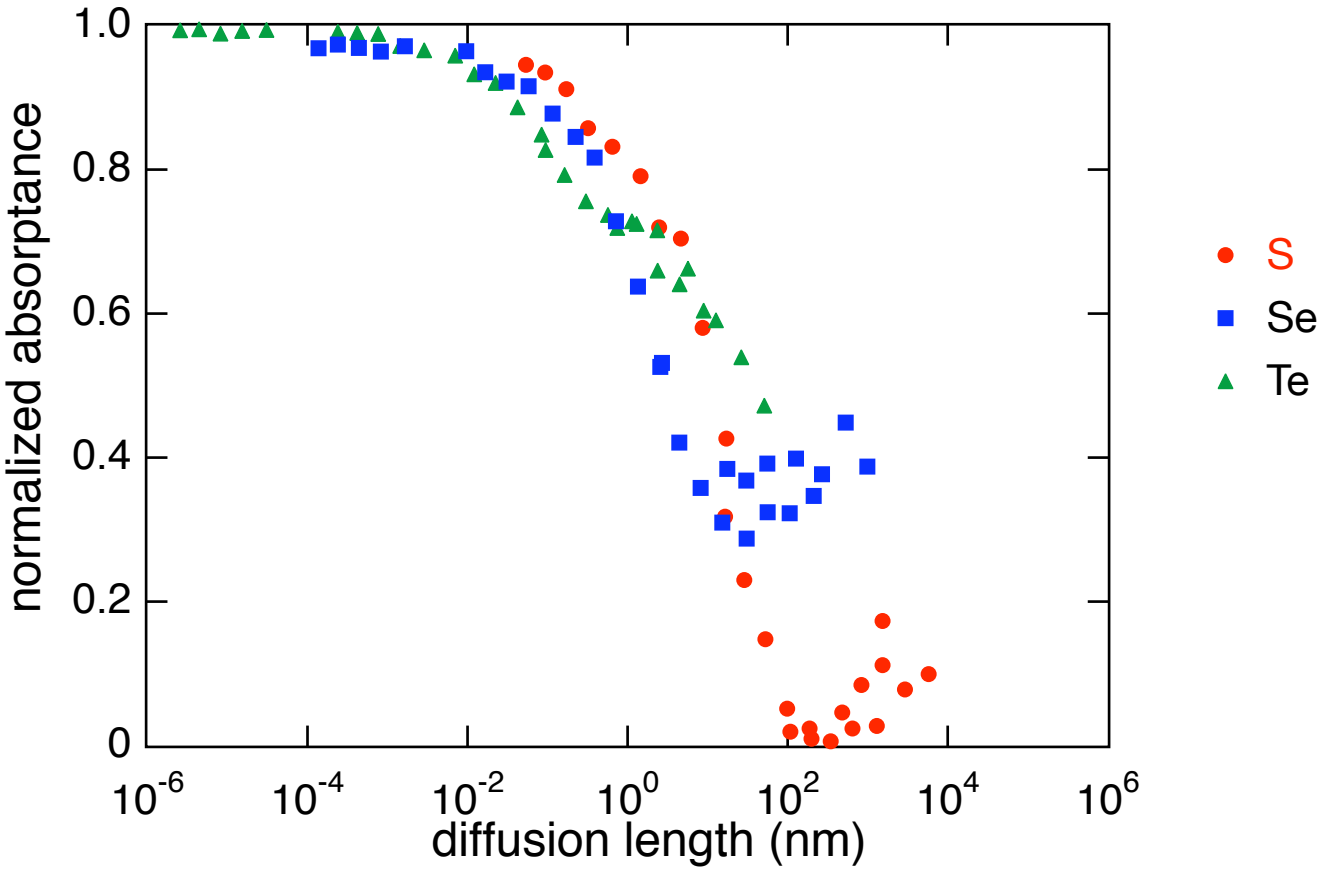
Rough surfaces → Hard to characterize


1.0
0.8
0.6
0.4
0.2
0.0
absorptance
0
1
2
3
wavelength (μm)
Te
SF6
Se
crystalline
silicon

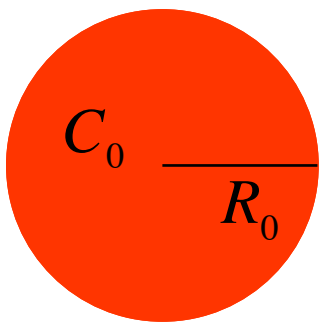

1.0
0.8
0.6
0.4
0.2
0.0
absorptance
0
1
2
3
wavelength (μm)
Si:Te
Si:Se
Si:S

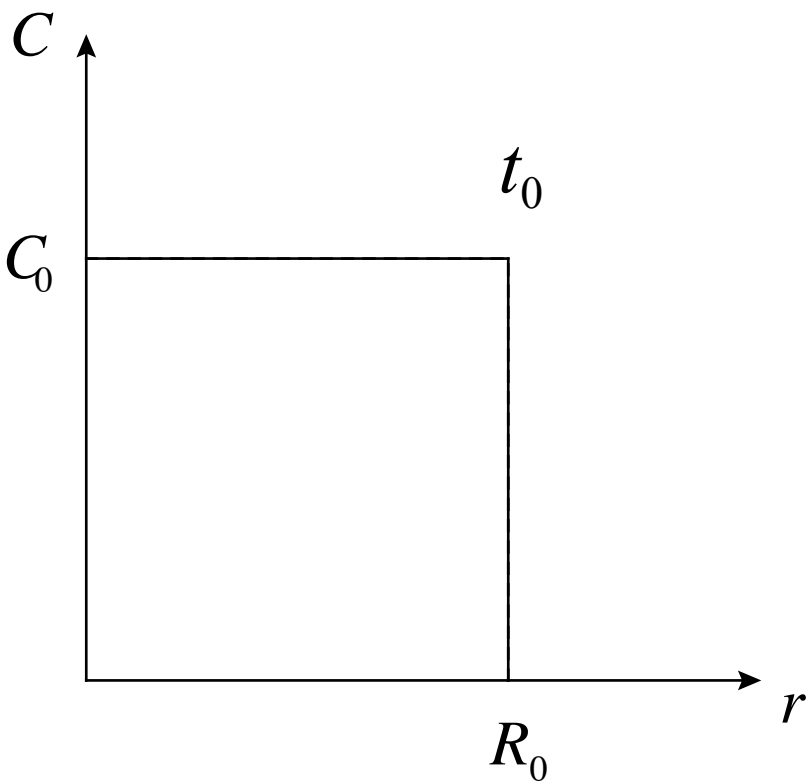


$$\text{diffusion length} = \sqrt{D_i t} = f(T,t)$$


1.0
0.8
0.6
0.4
0.2
0
normalized absorptance
10^{-6}
10^{-4}
10^{-2}
10^{0}
10^{2}
10^{4}
10^{6}
diffusion length (nm)
S
Se
Te

Could this diffusion-related drop in absorptance be governed by grain size?





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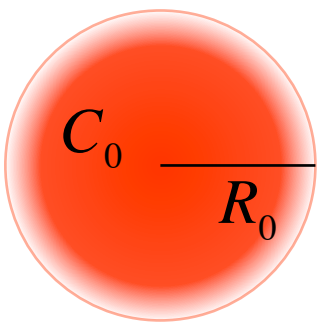

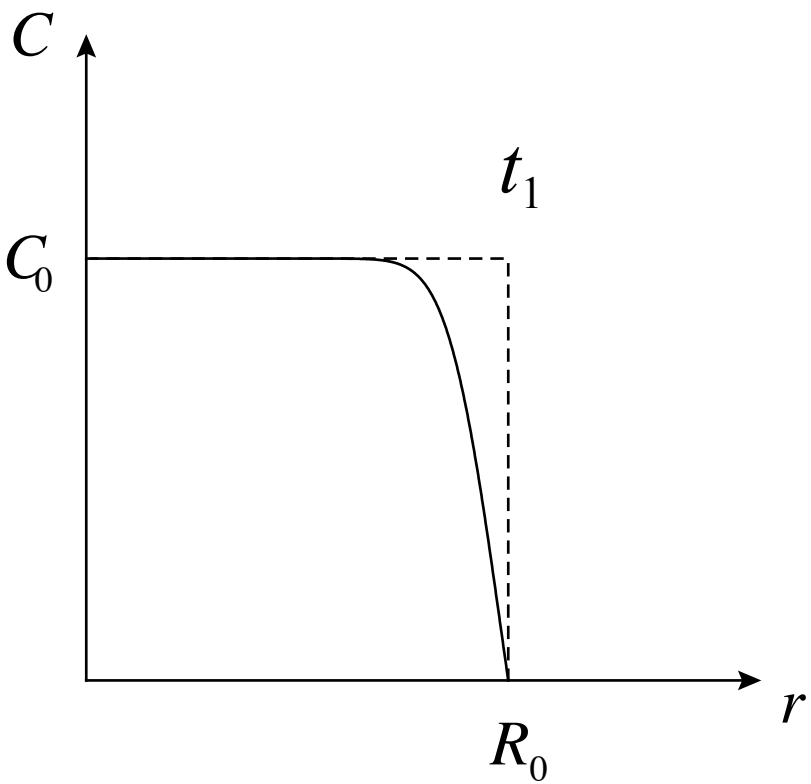

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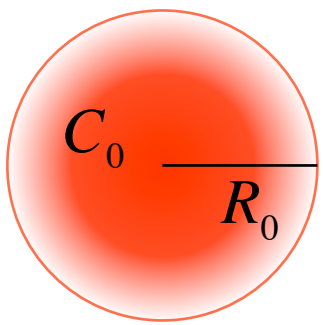

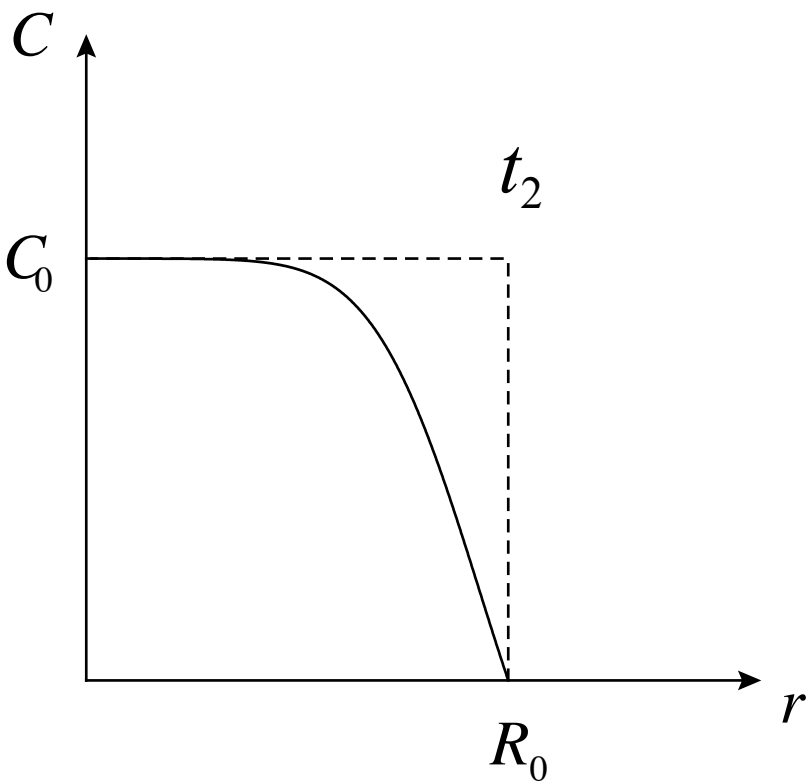

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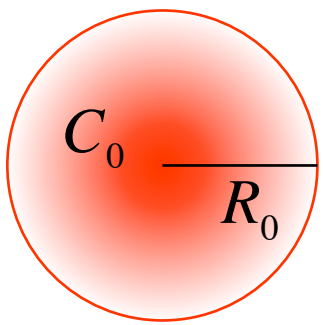
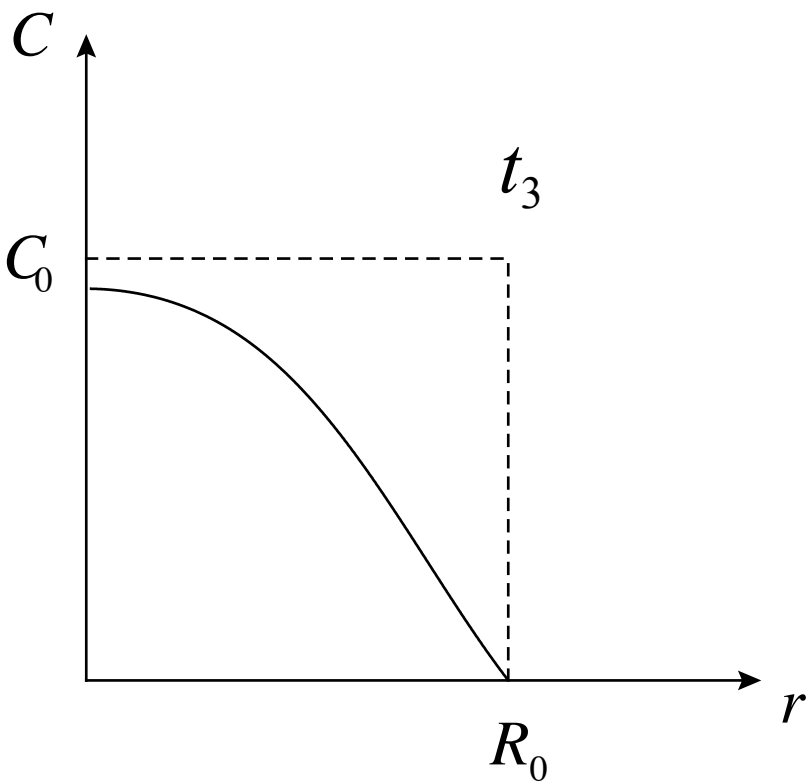
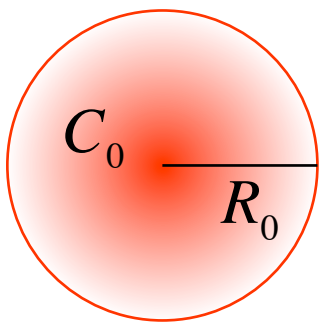
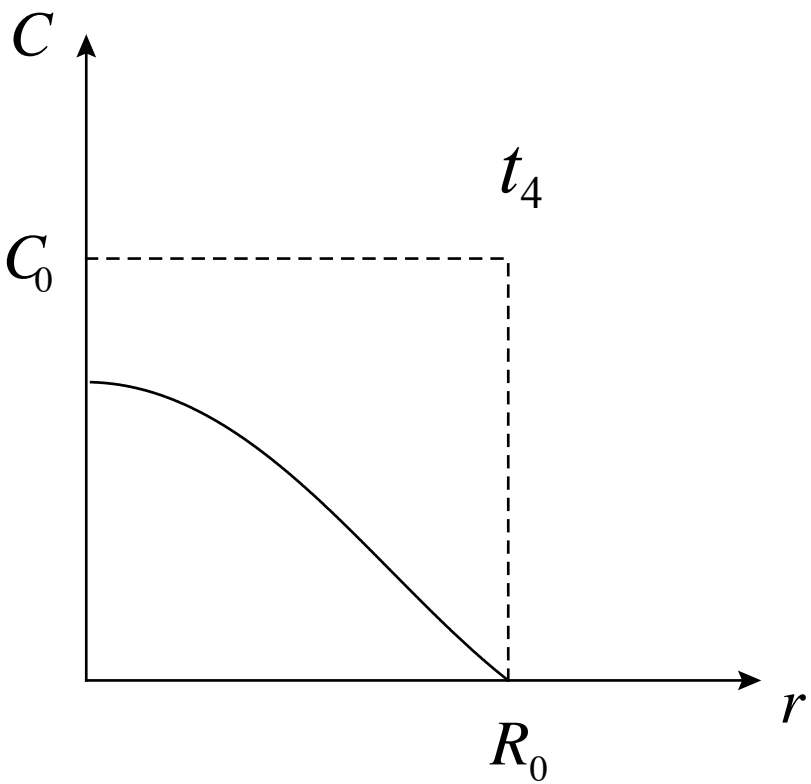


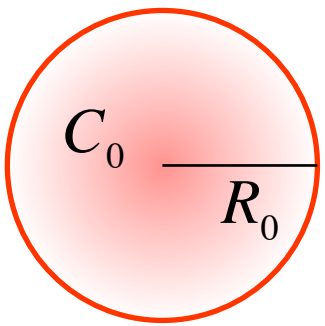


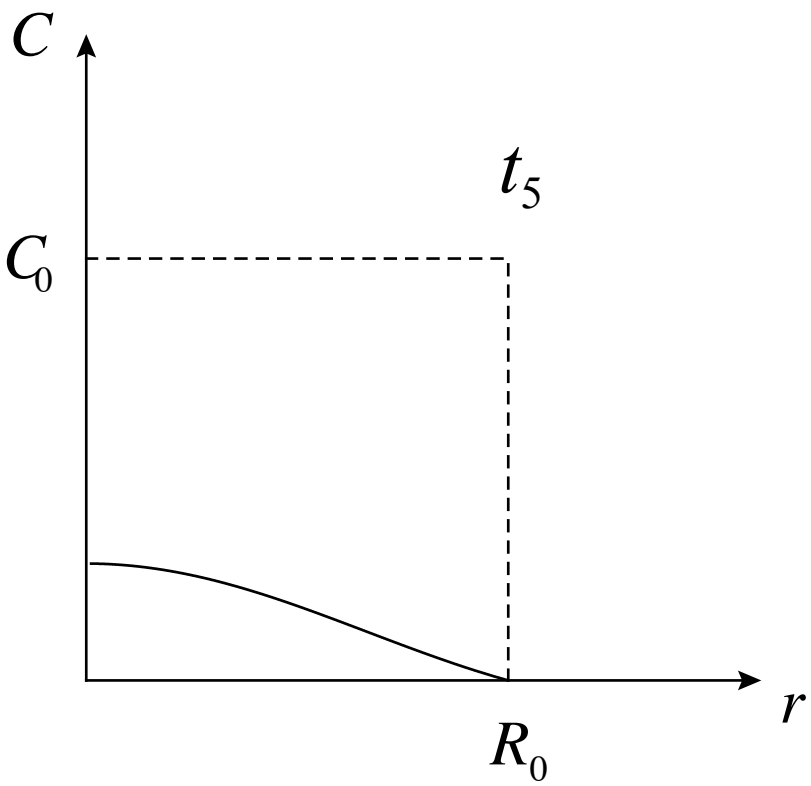
Could this diffusion-related drop in absorptance be governed by grain size?



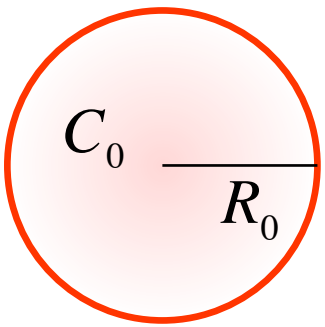


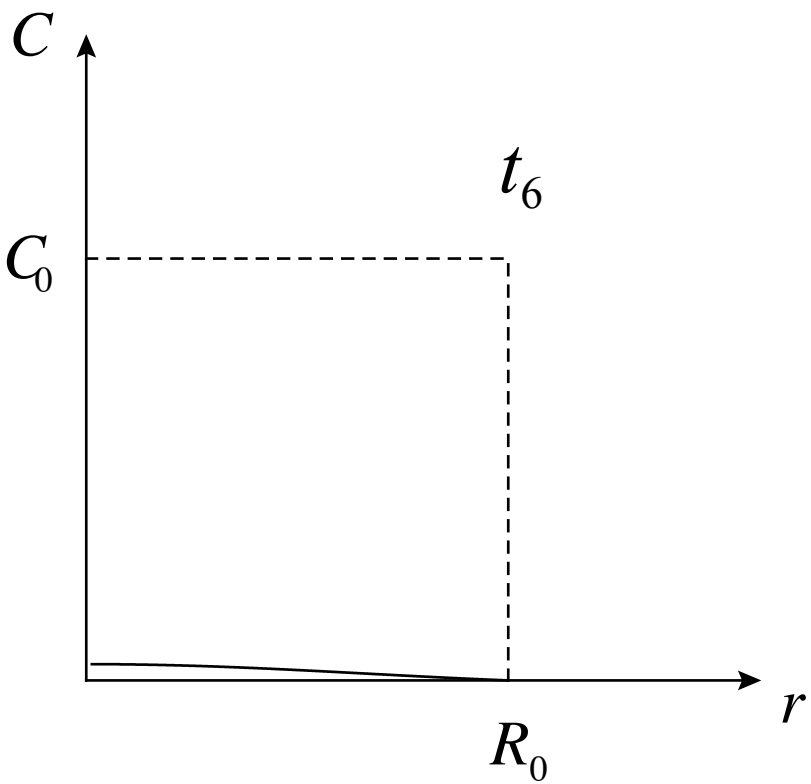
Could this diffusion-related drop in absorptance be governed by grain size?

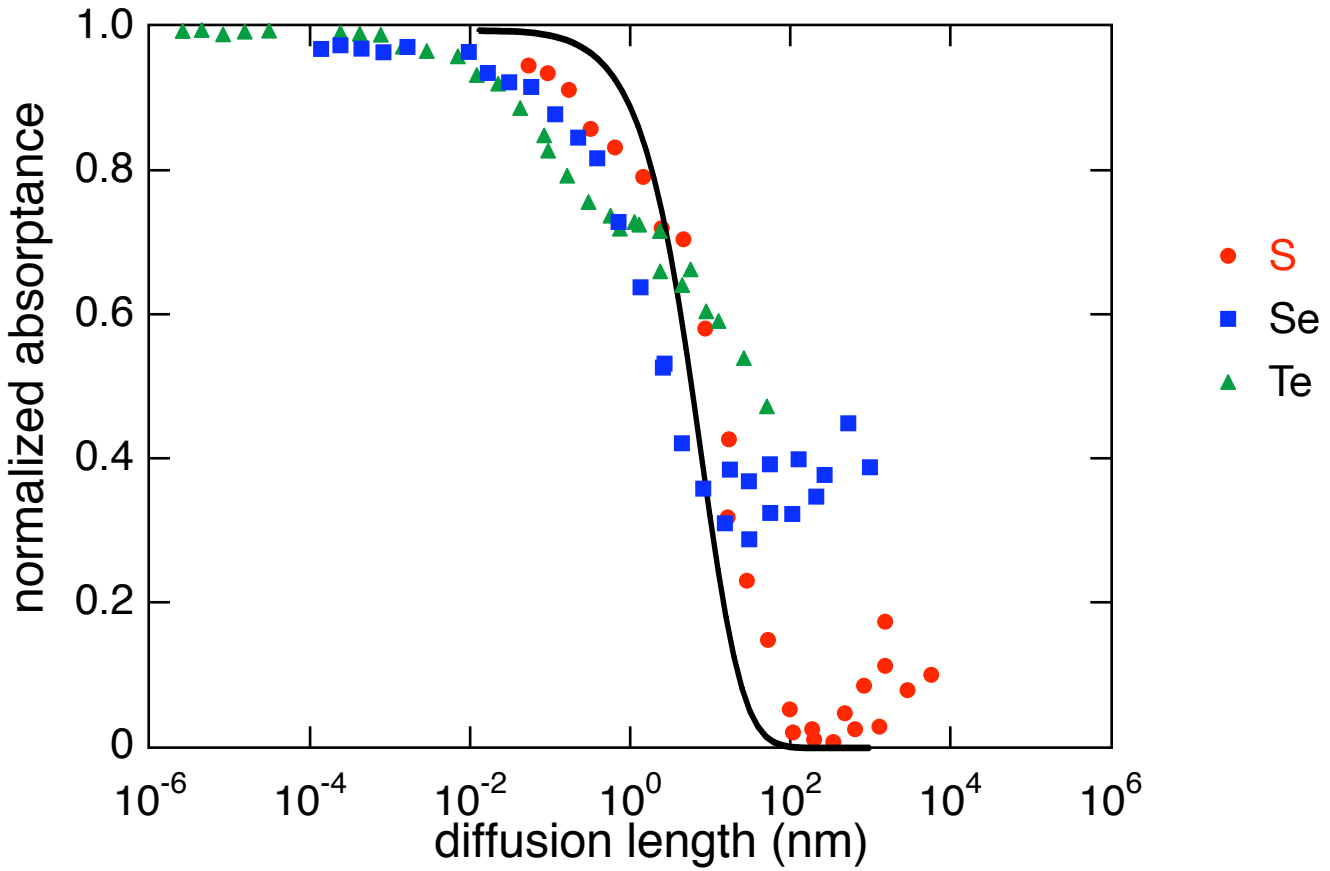




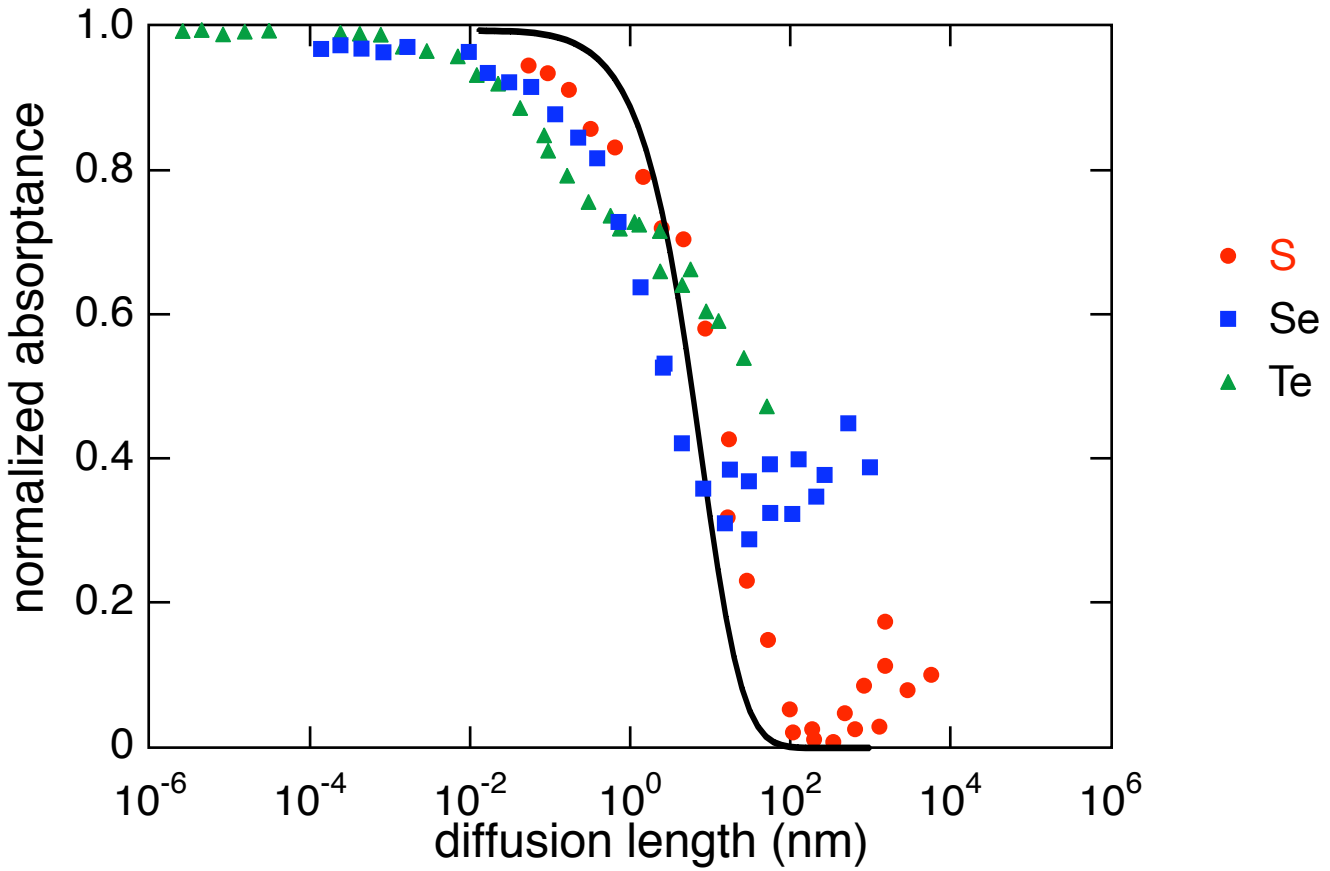
Could this diffusion-related drop in absorptance be governed by grain size?

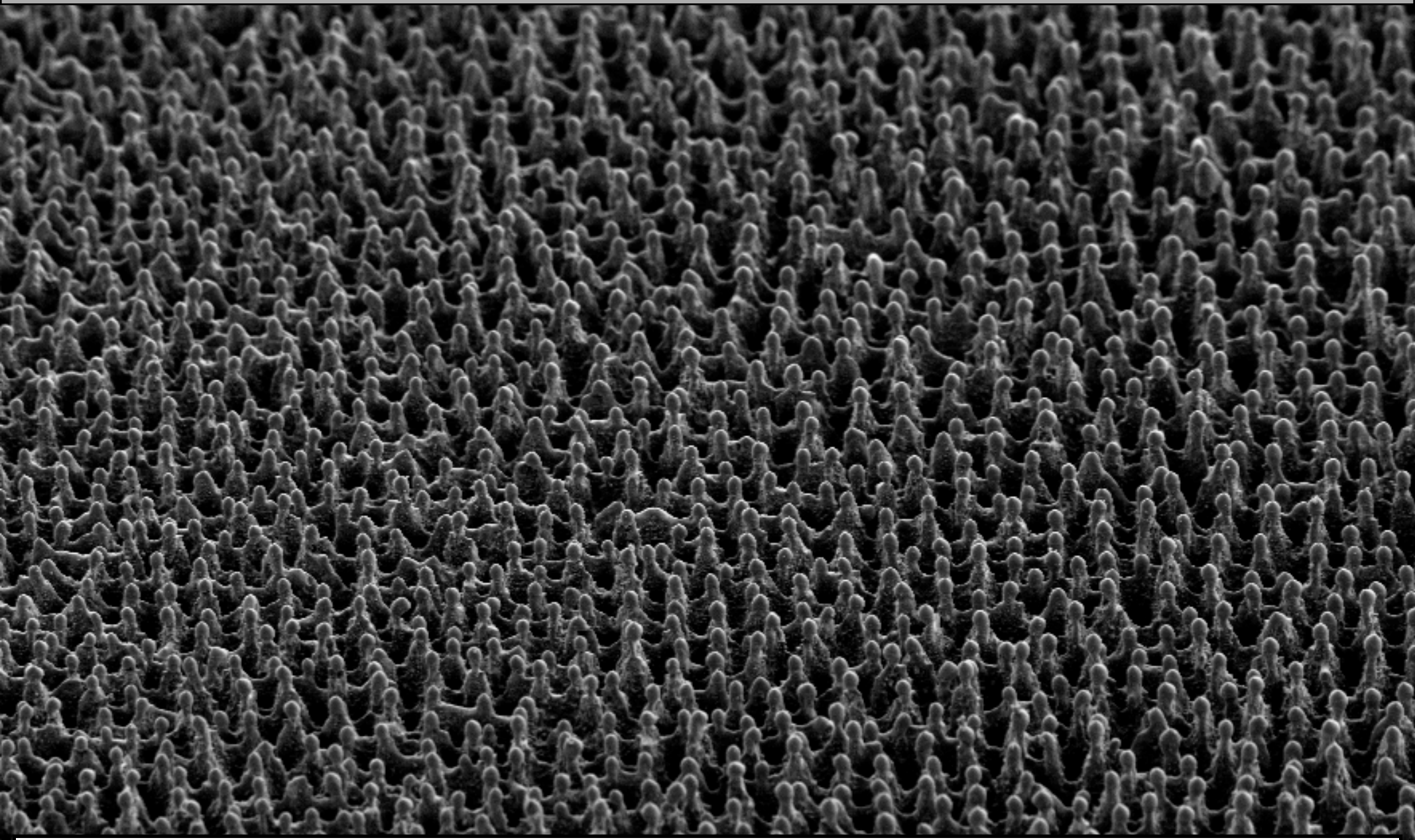




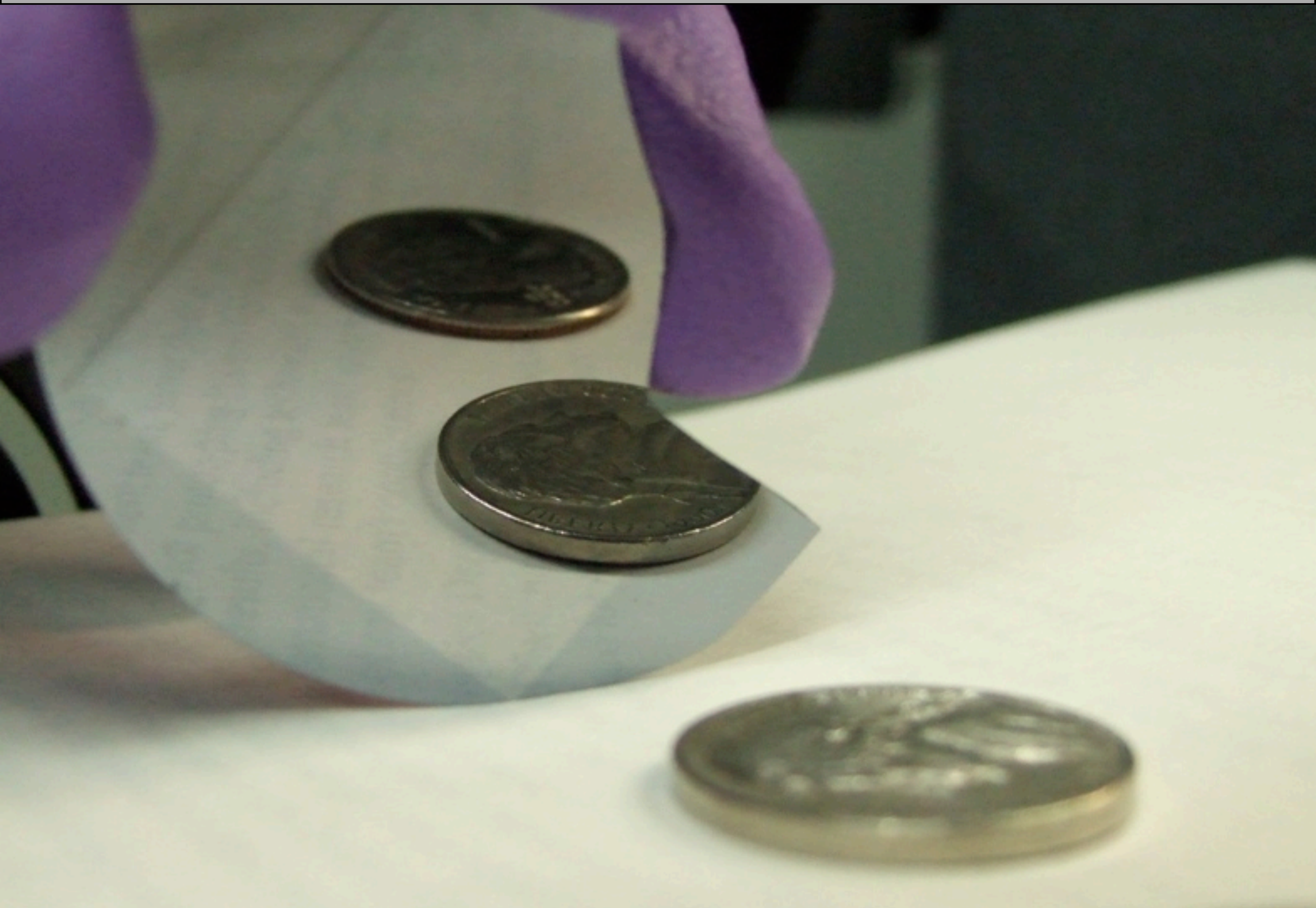

1.0
0.8
0.6
0.4
0.2
0
normalized absorptance
10^{-6}
10^{-4}
10^{-2}
10^{0}
10^{2}
10^{4}
10^{6}
diffusion length (nm)
S
Se
Te

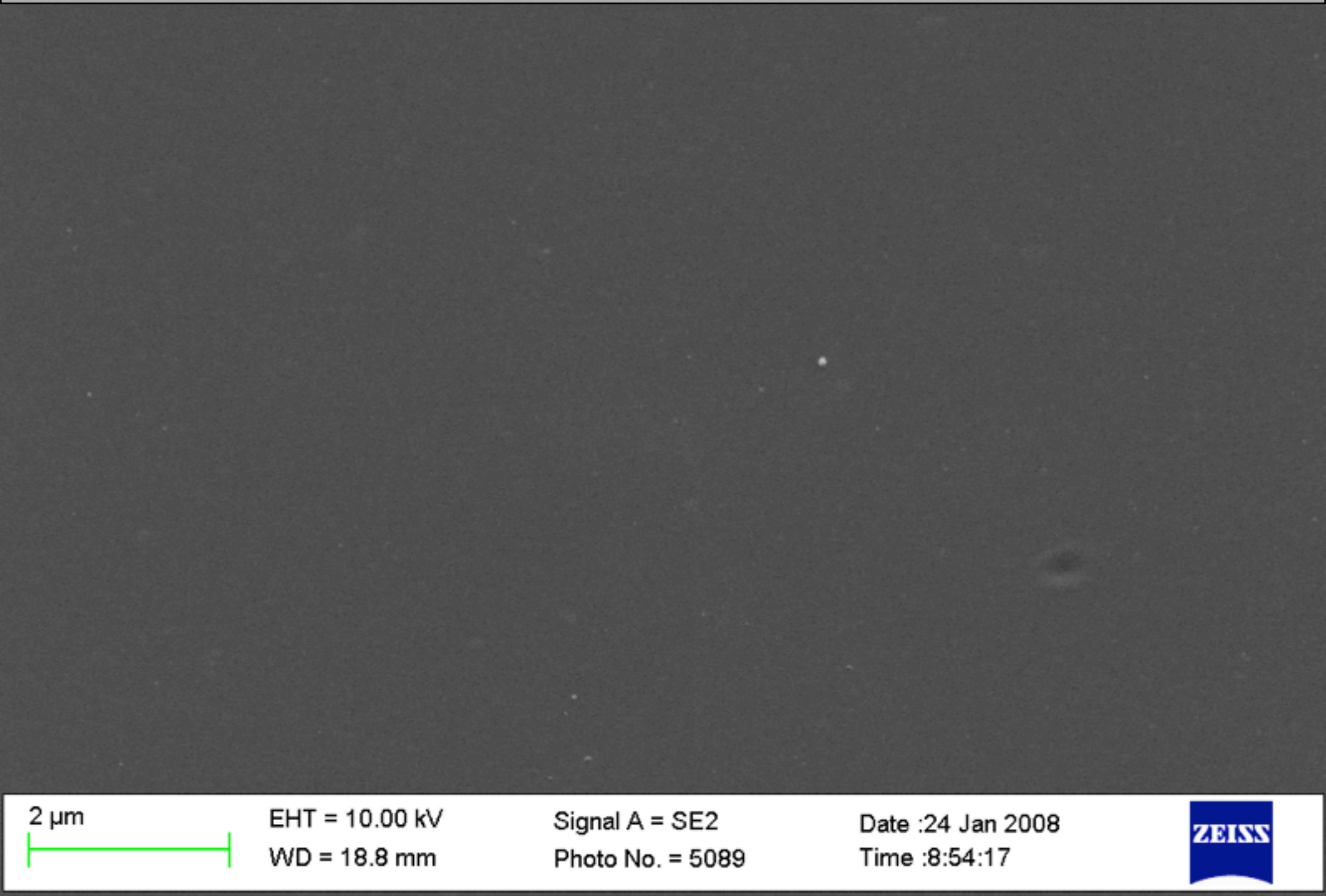
Conclusion: diffusion is the dominant mechanism involved in deactivation of optical response

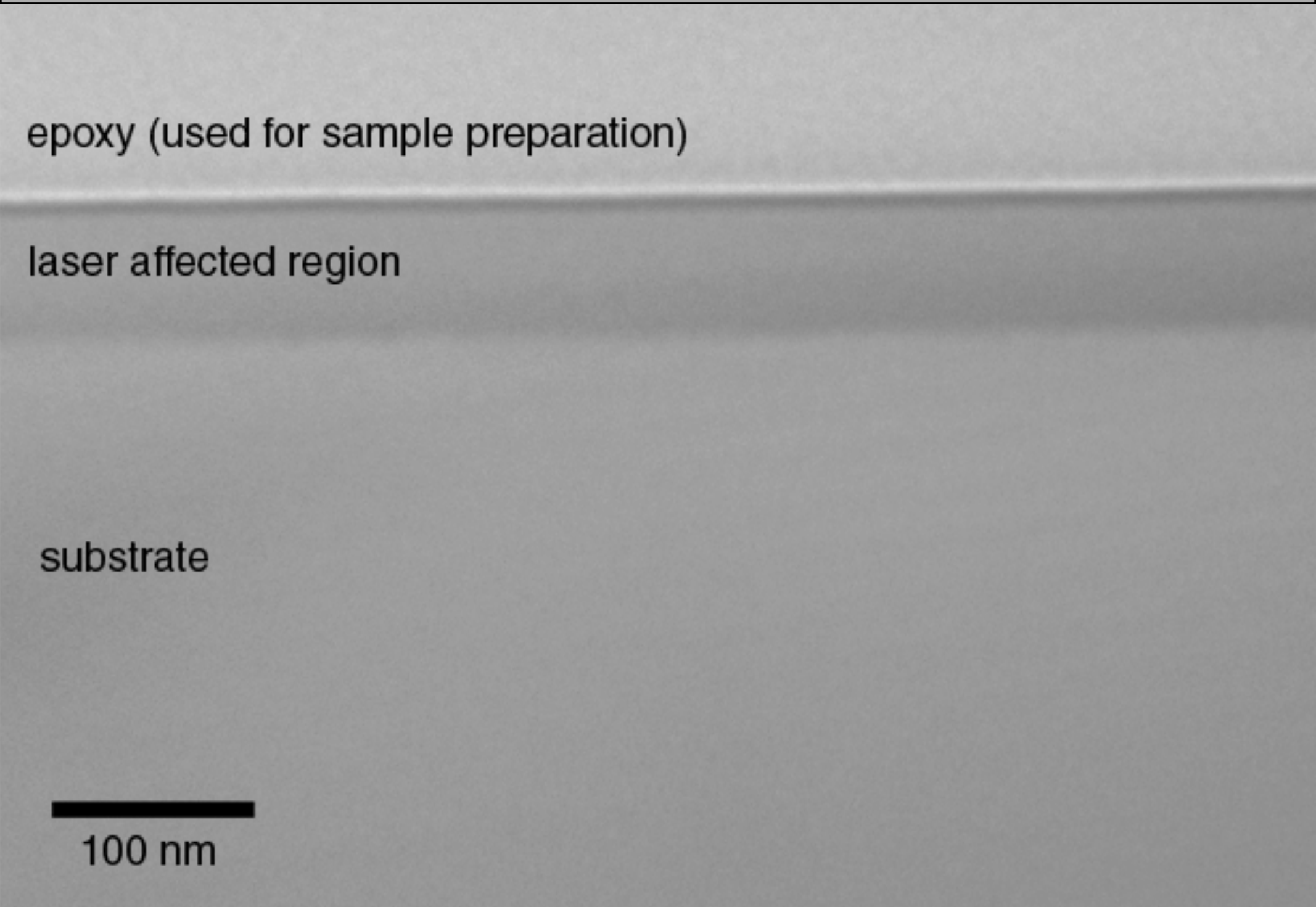


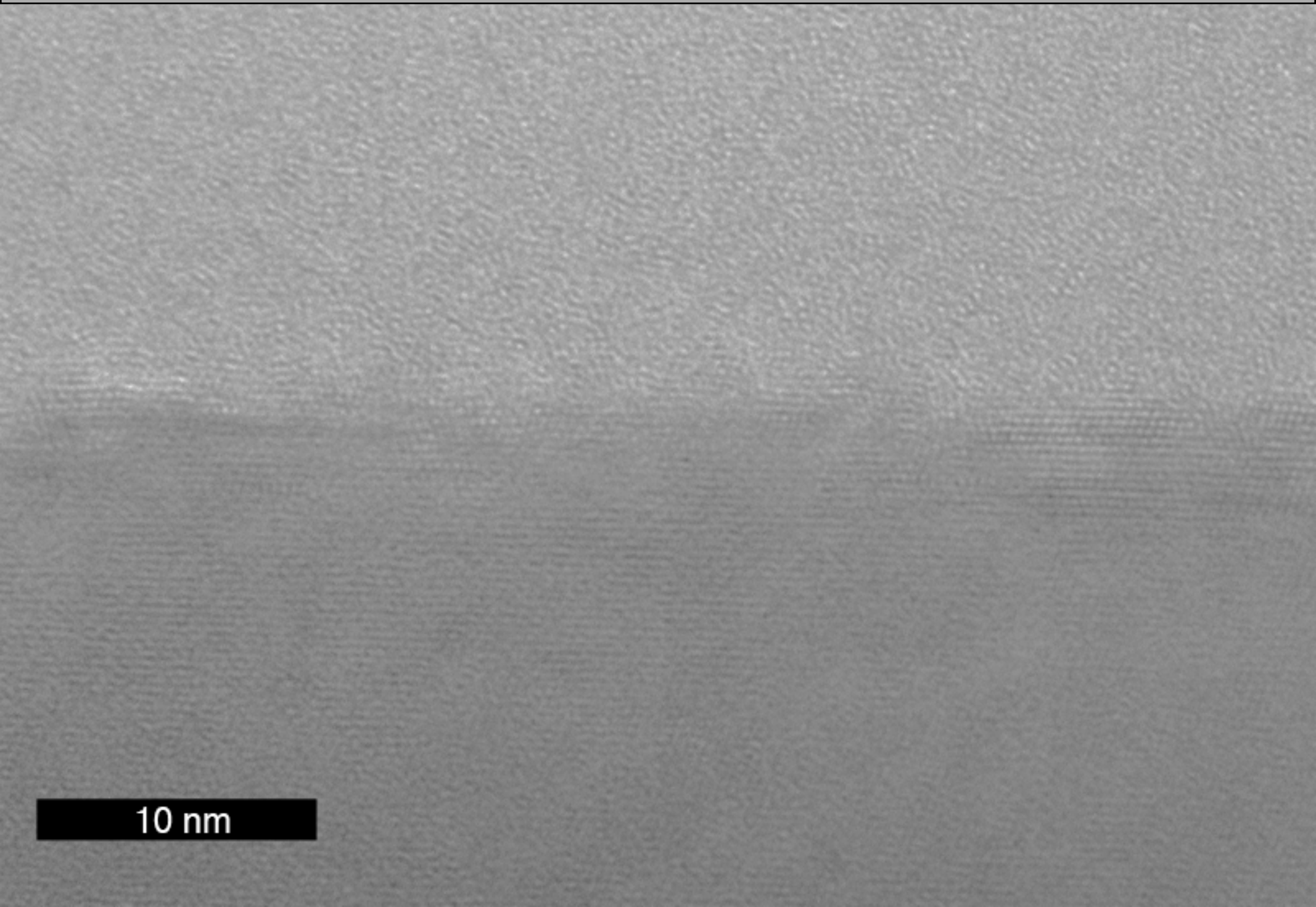


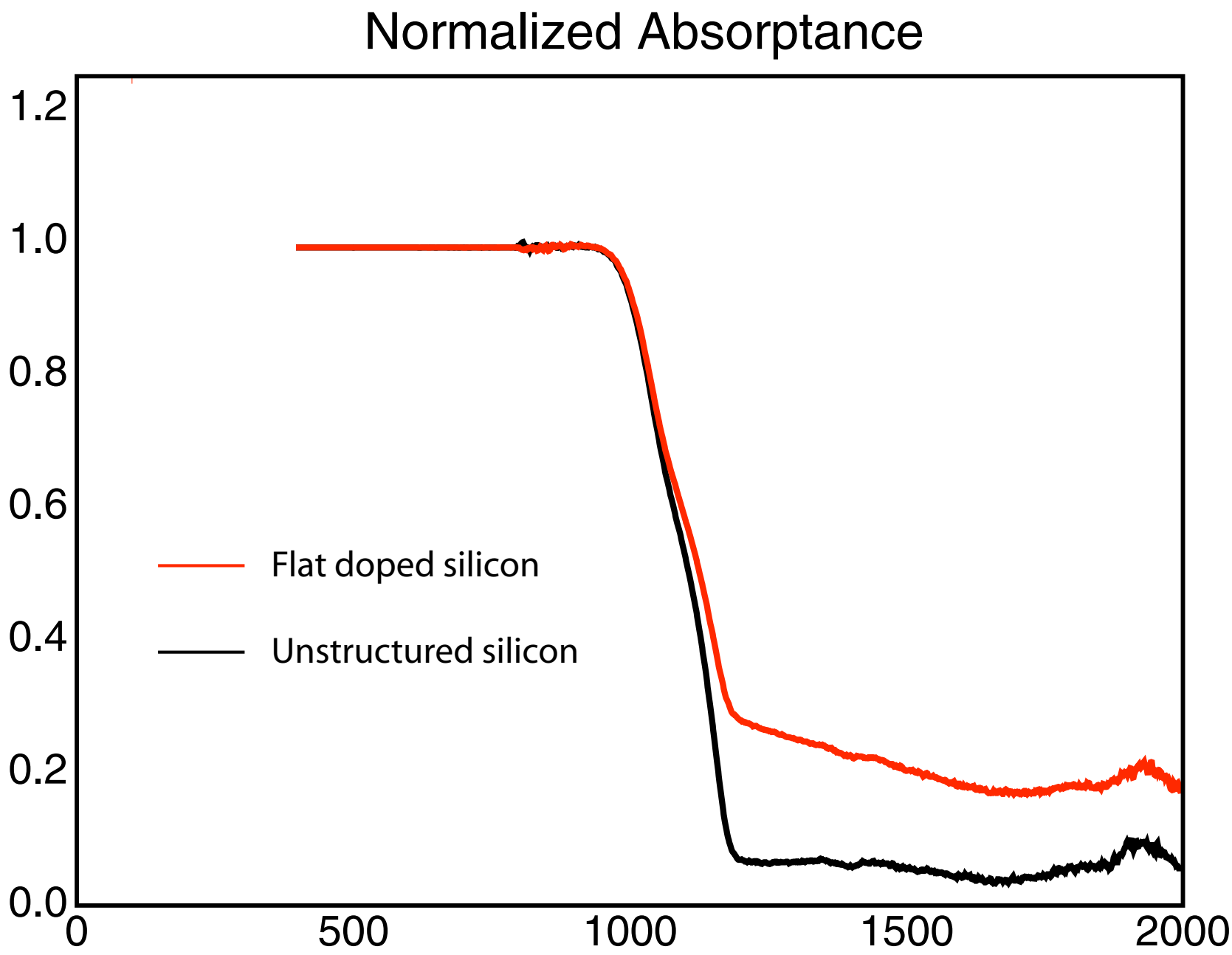
Rough surfaces → Hard to characterize




2 µm
EHT = 10.00 kV
WD = 18.8 mm
Signal A = SE2
Photo No. = 5089
Date :24 Jan 2008
Time :8:54:17
ZEISS

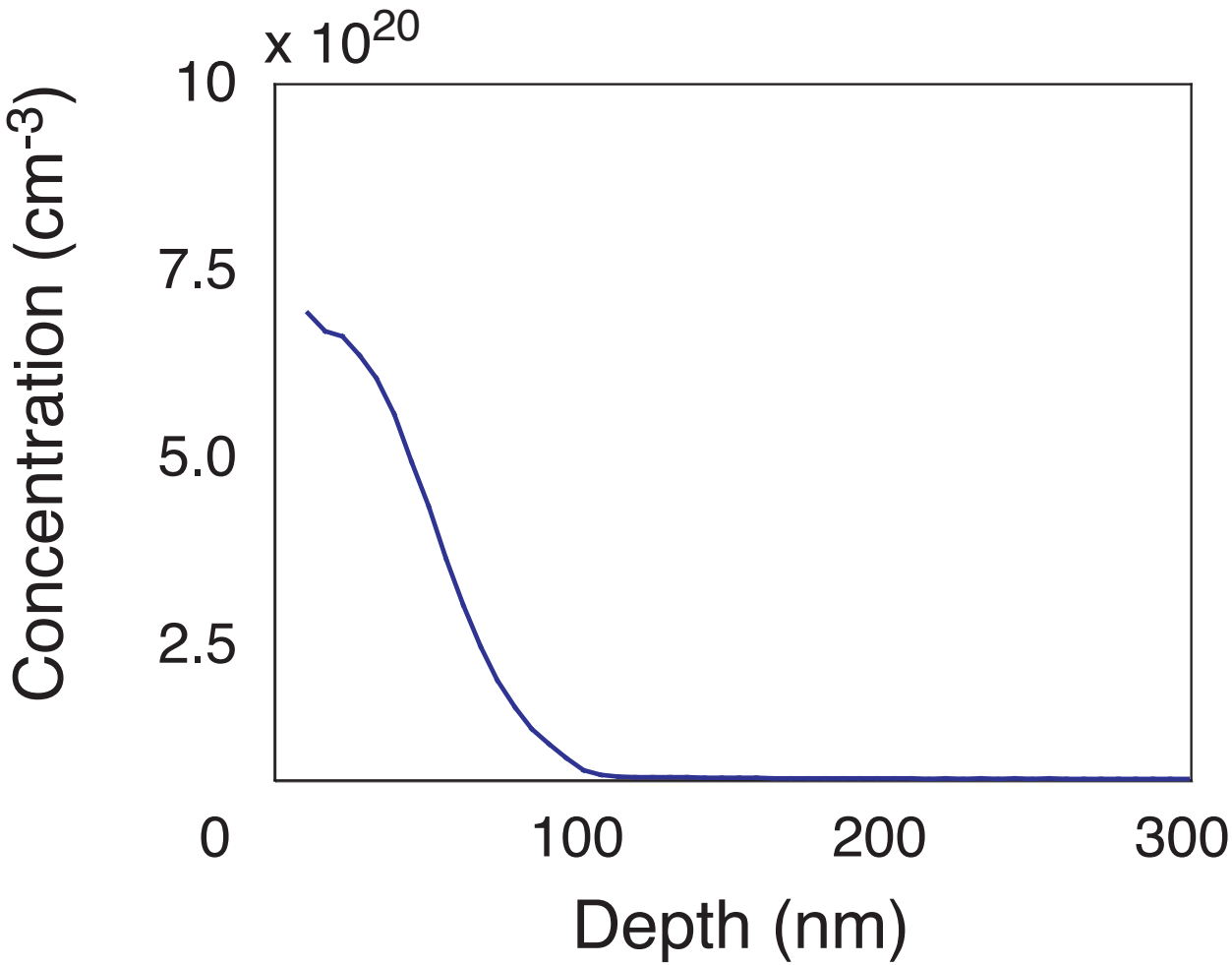

epoxy (used for sample preparation)
laser affected region
substrate
100 nm


10 nm


Normalized Absorptance
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
500
1000
1500
2000
Flat doped silicon
Unstructured silicon

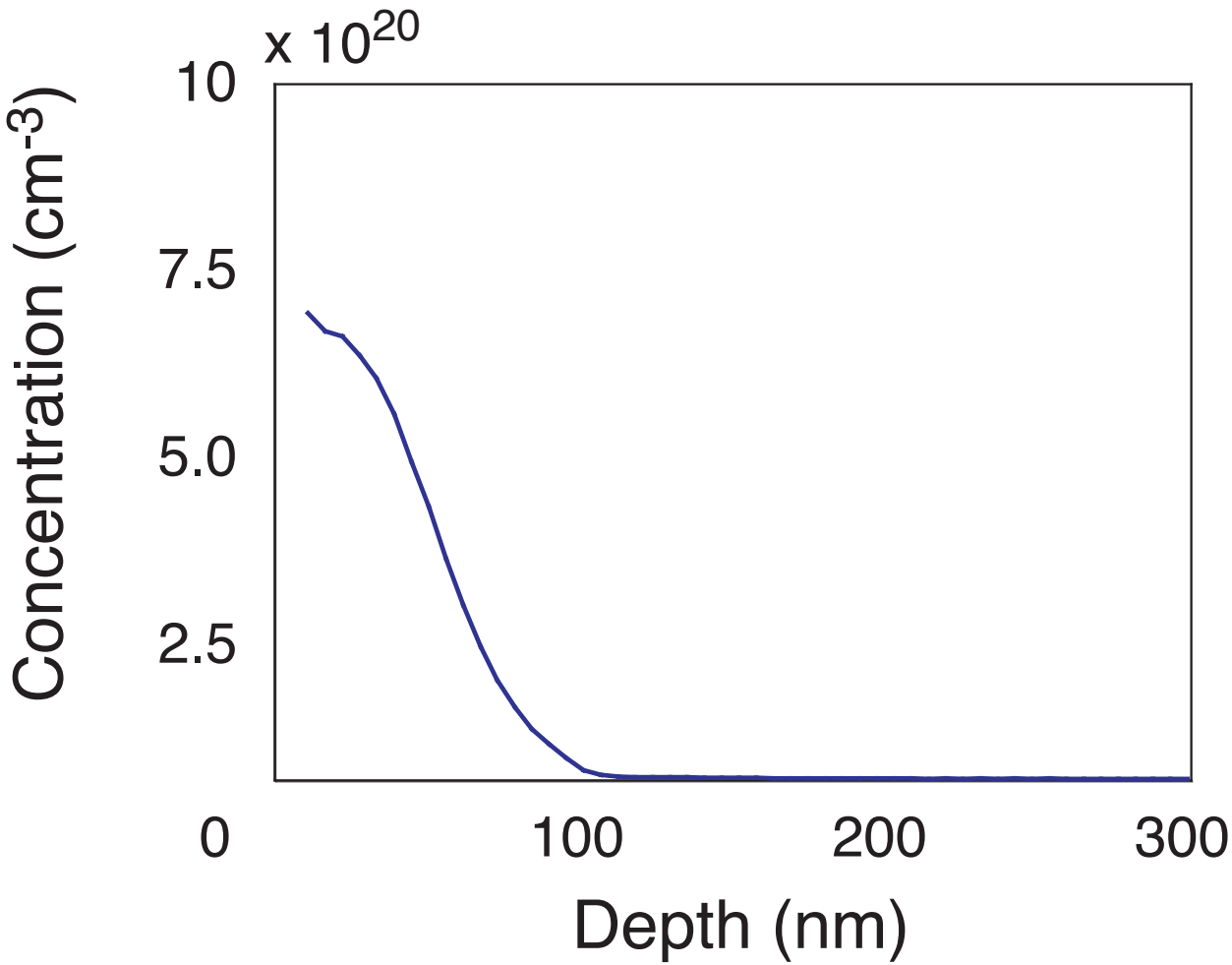
New characterization techniques

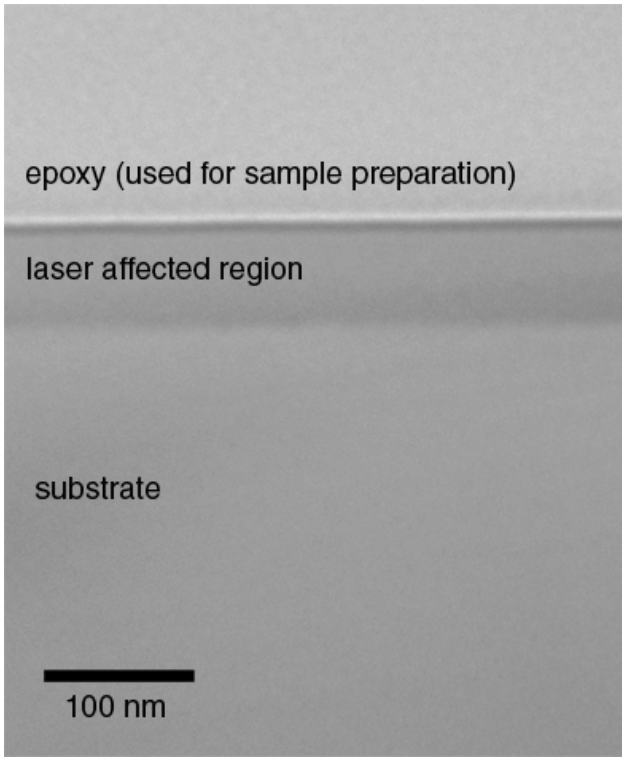
secondary ion mass spectroscopy (SIMS)

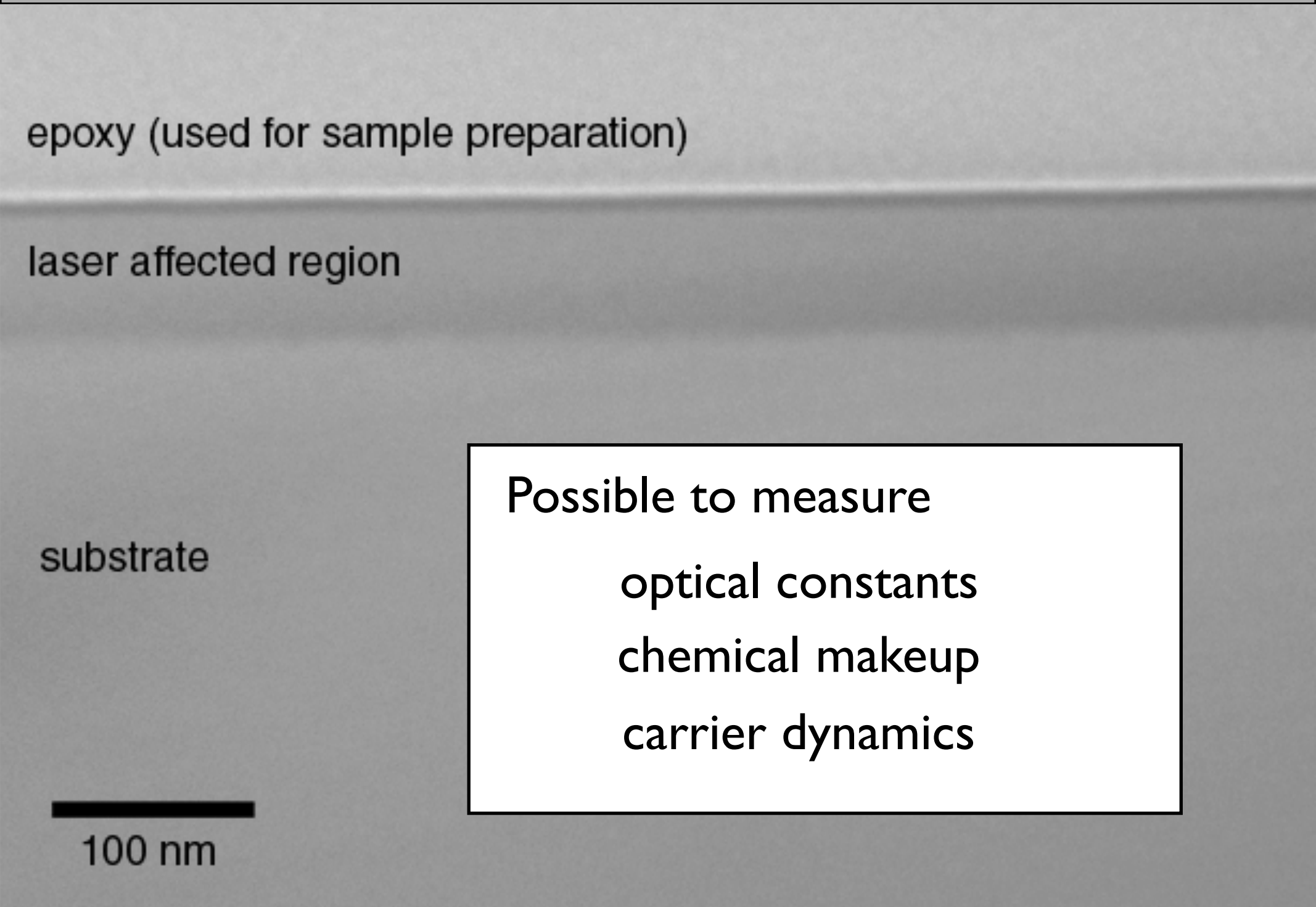


New characterization techniques

secondary ion mass spectroscopy (SIMS)







Possible to measure

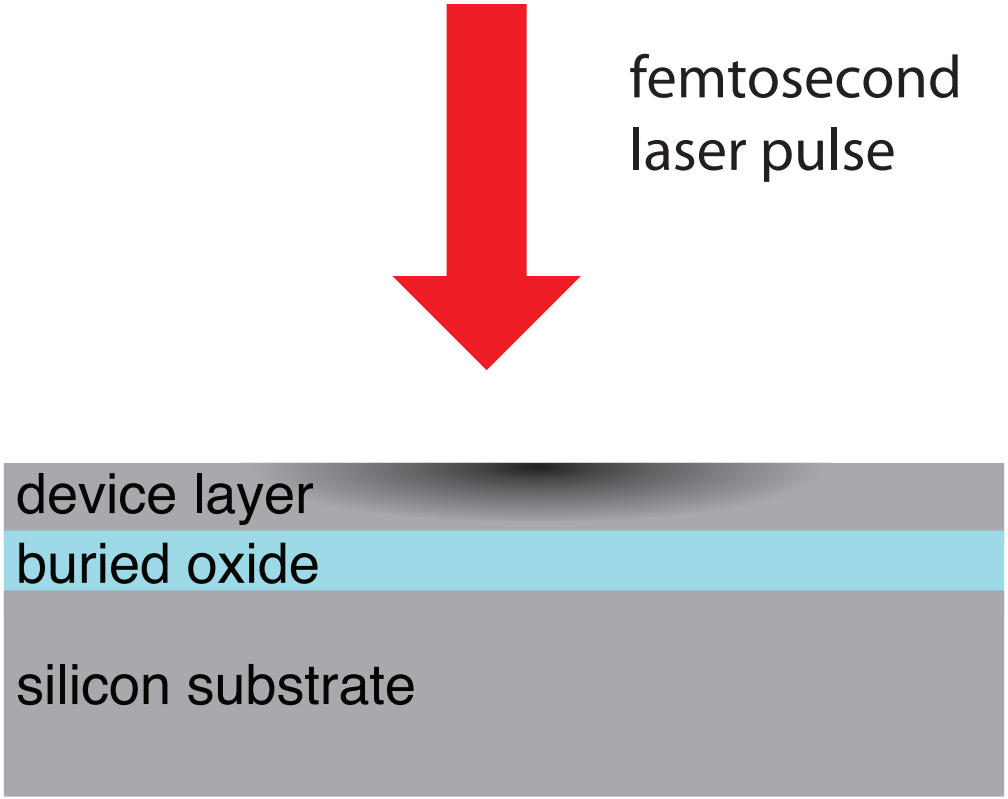
optical constants

chemical makeup

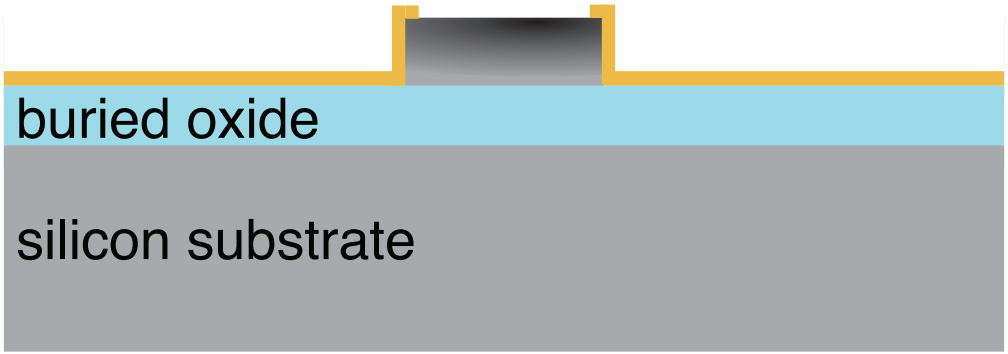
carrier dynamics

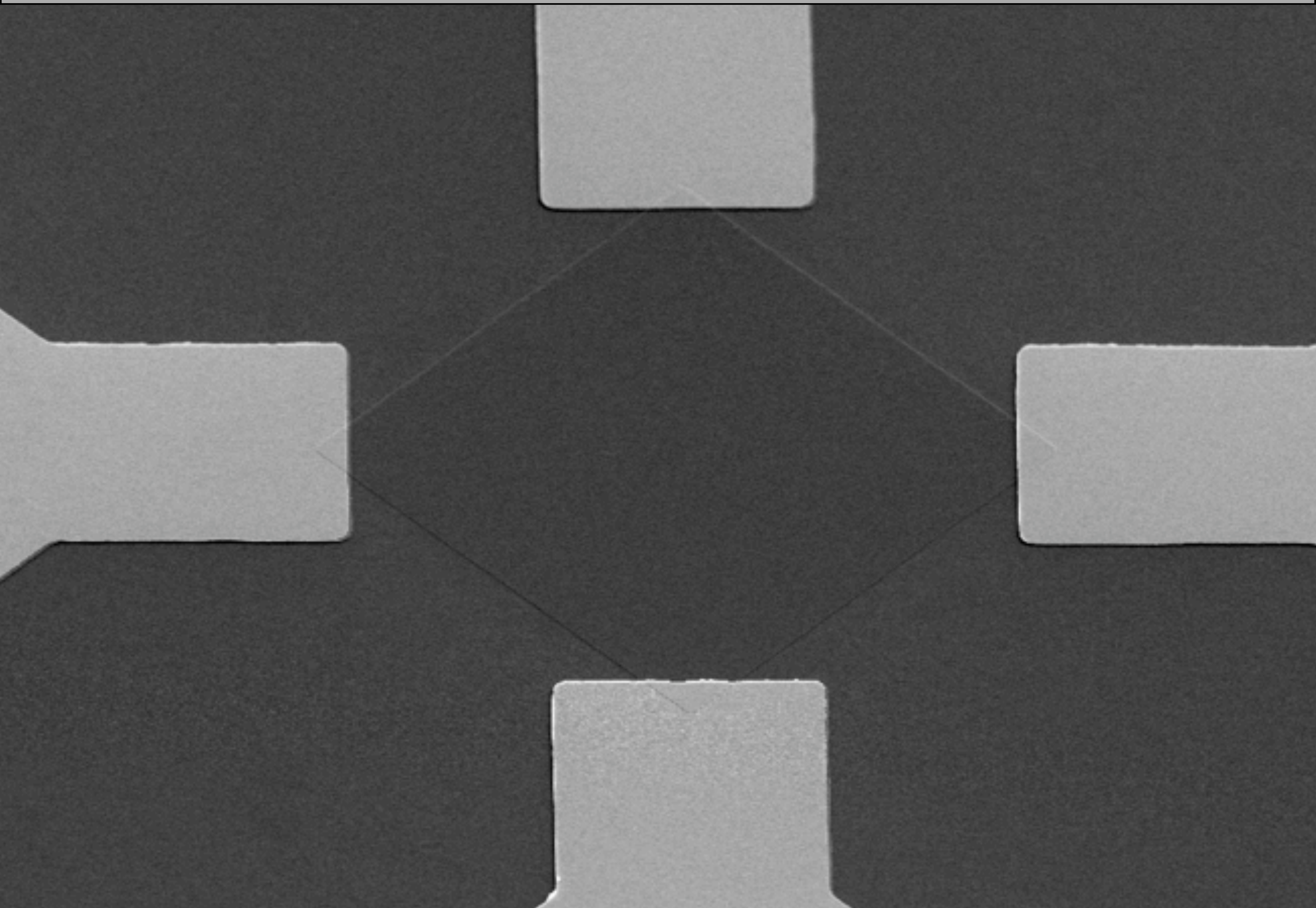
Isolate surface properties

Isolate surface properties



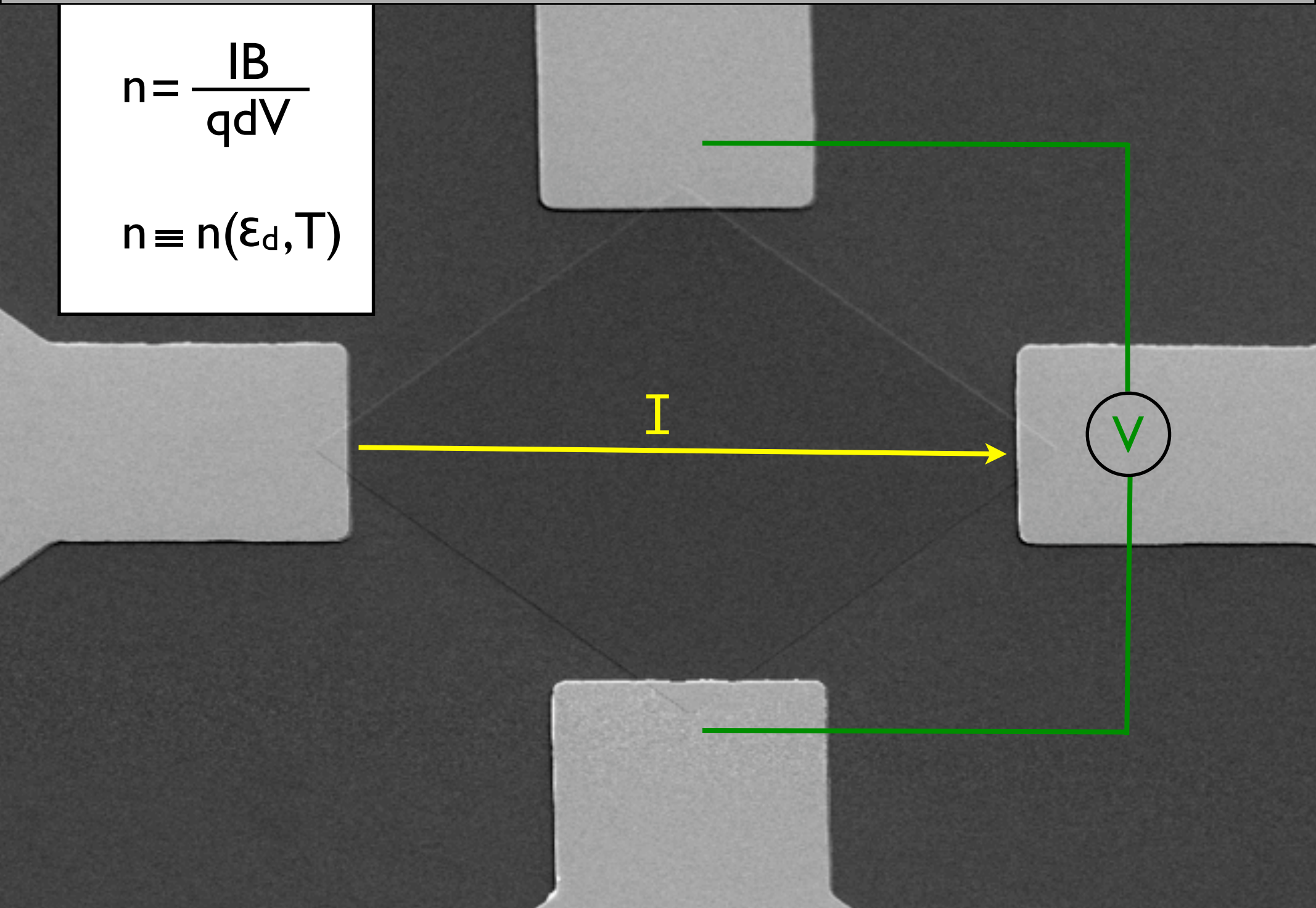
Isolate surface properties



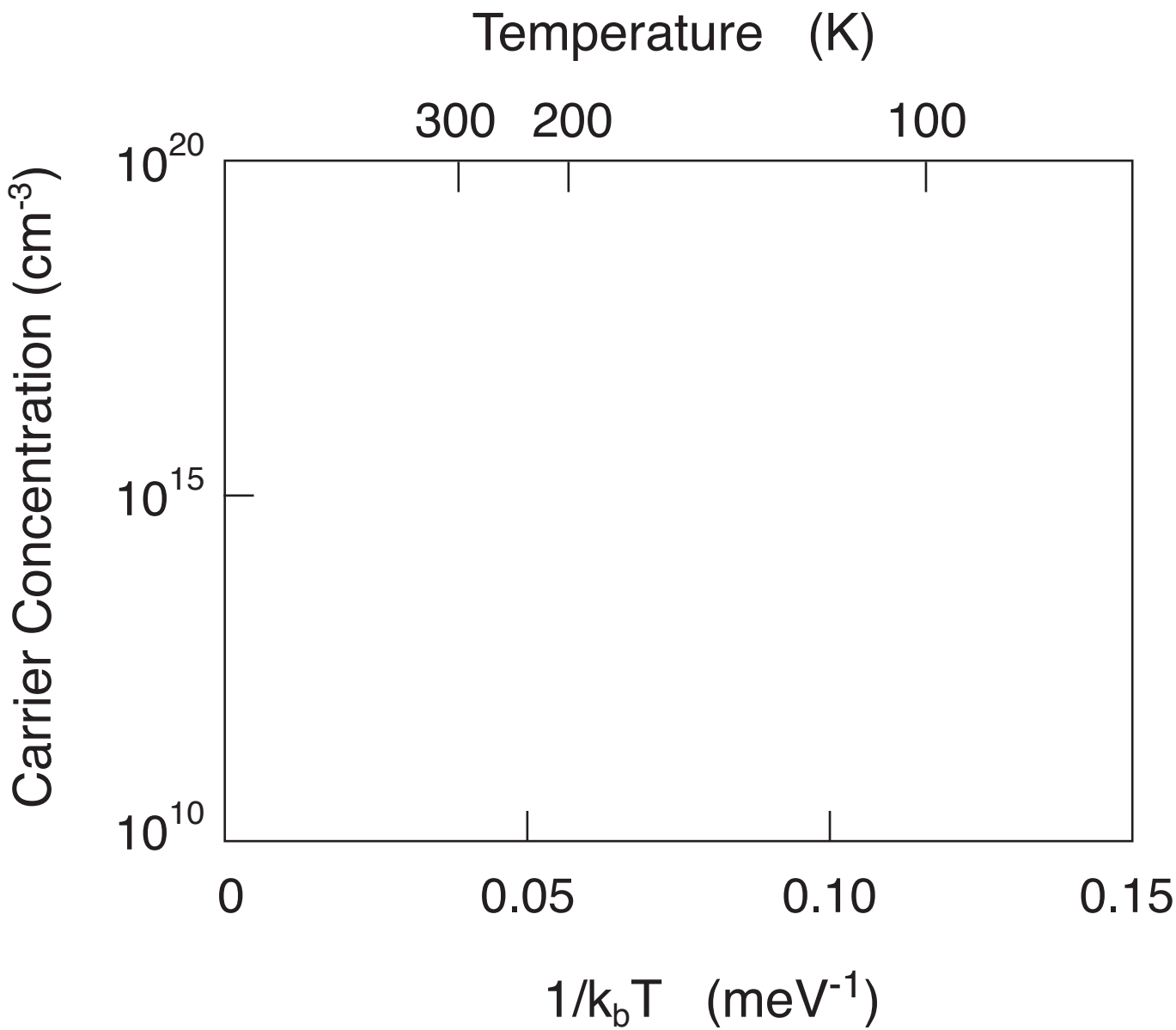


$$n = \frac{IB}{qdV}$$

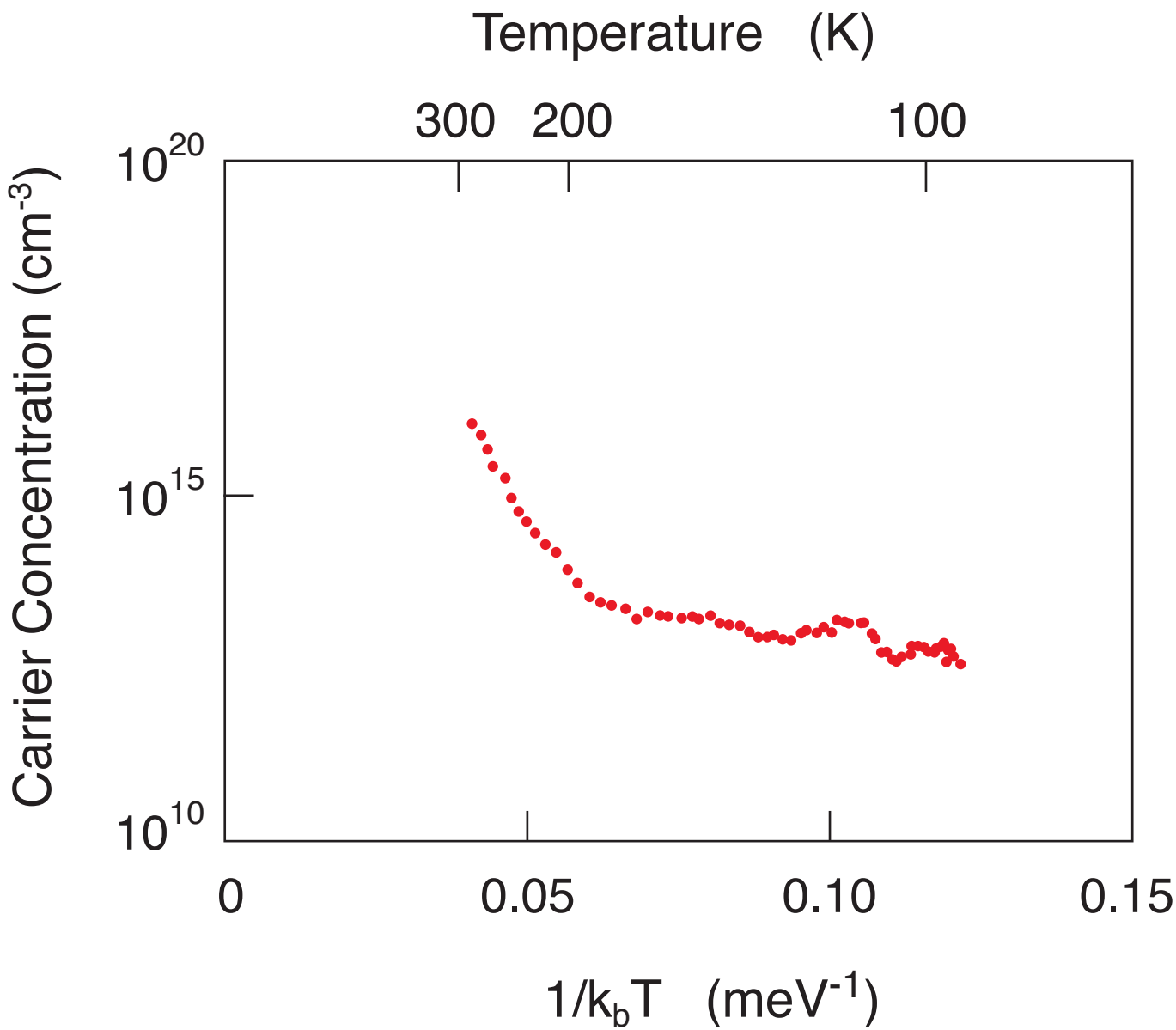
$$n \equiv n(\varepsilon_d, T)$$



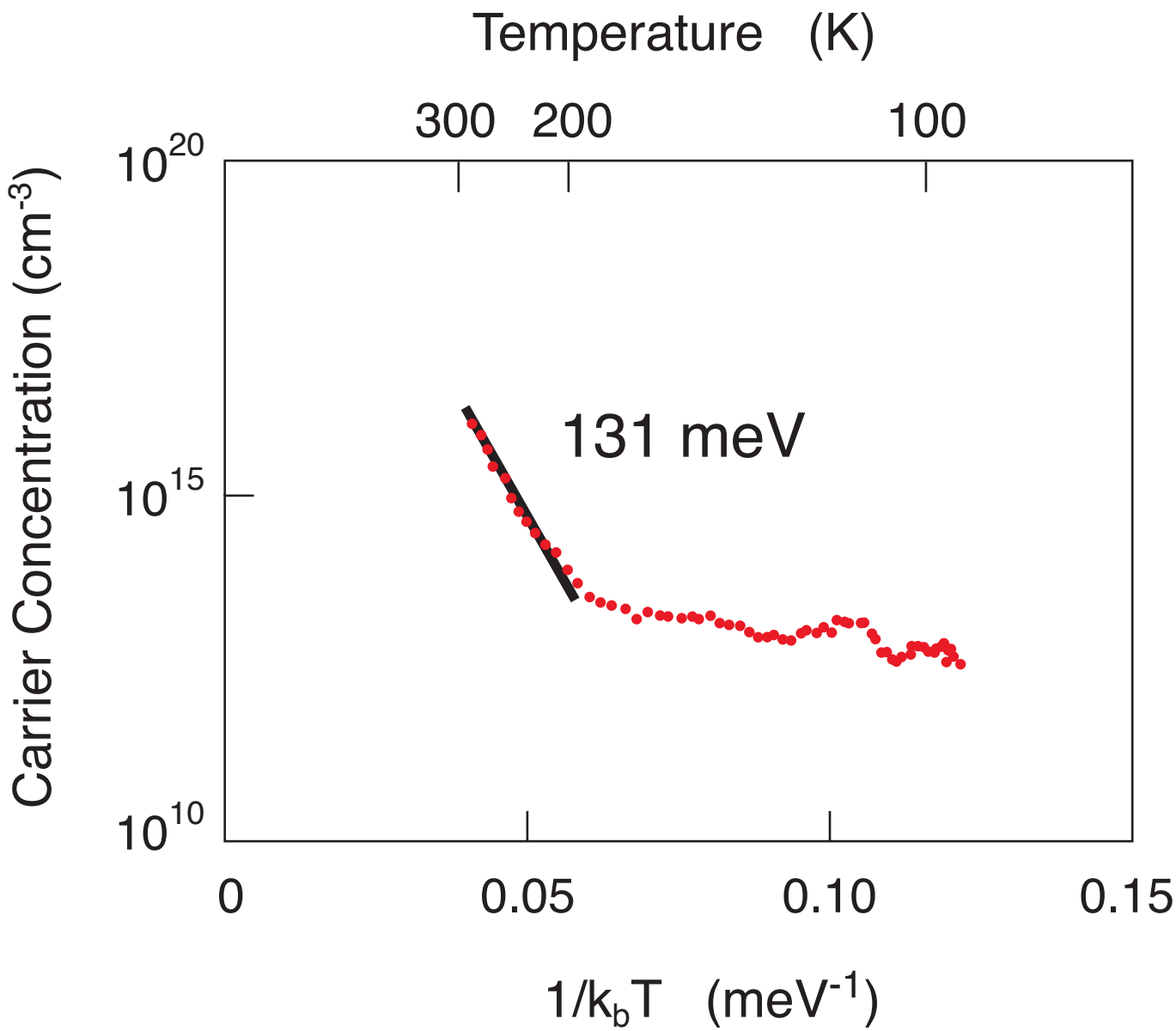
Dopant levels from Hall measurements



Dopant levels from Hall measurements

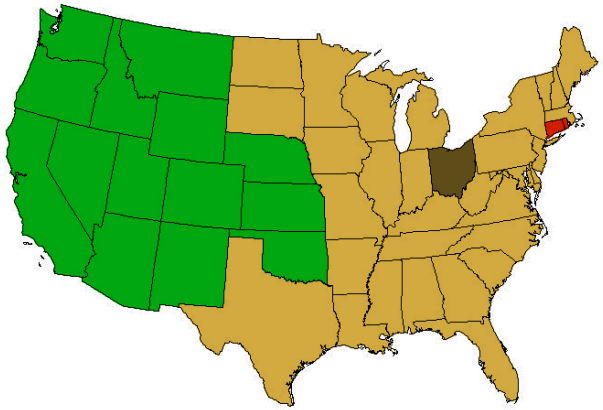


Dopant levels from Hall measurements



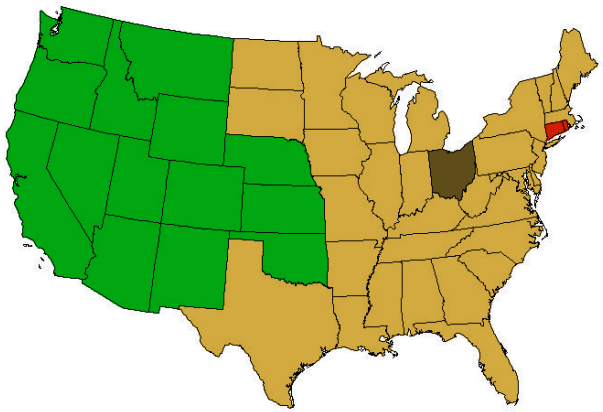
Conclusions

Conclusions

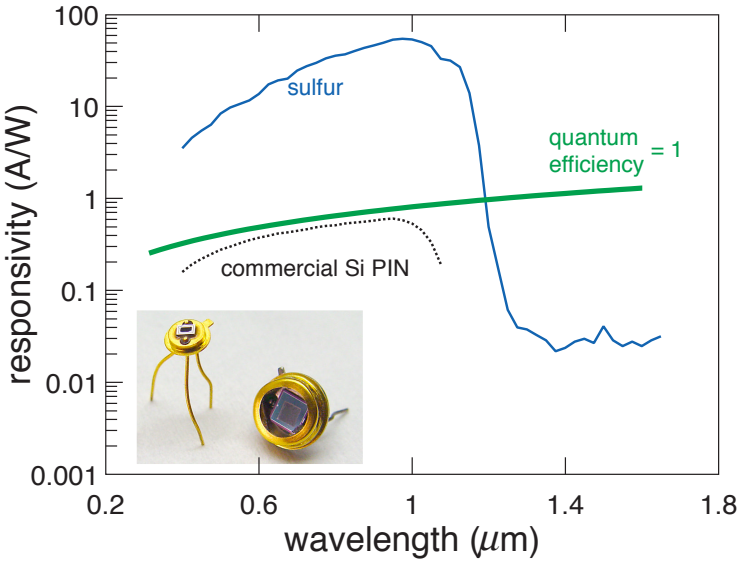


We need to extend silicon's reach

Conclusions

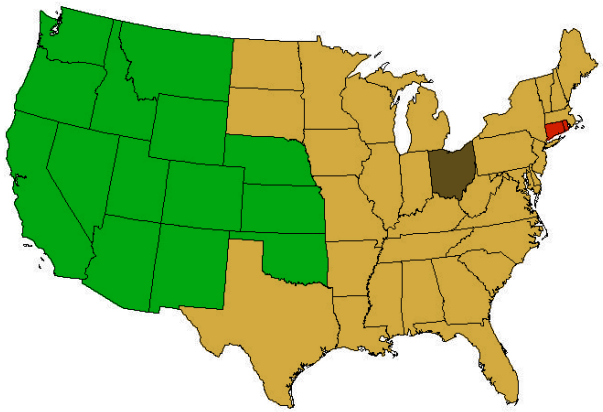


We need to extend silicon's reach

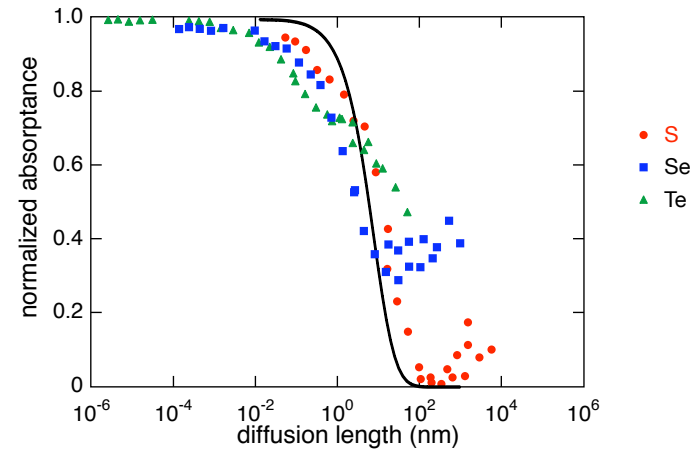


Non-equilibrium doping extends silicon's reach!

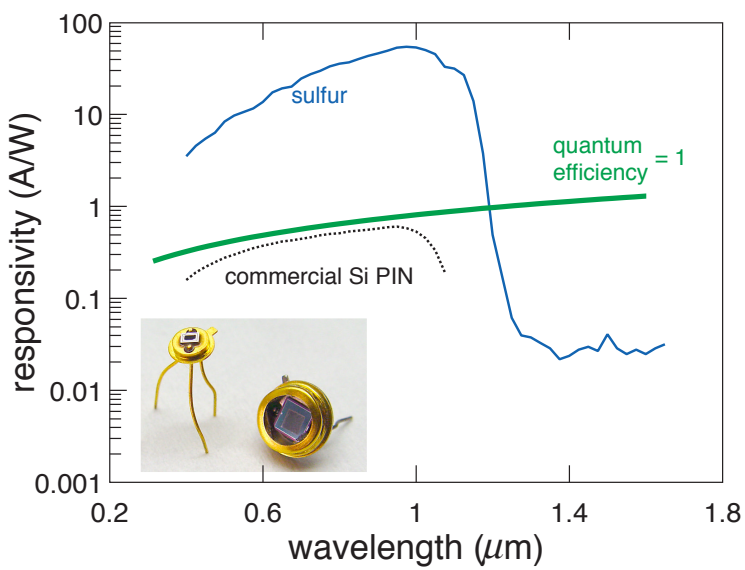
Conclusions



We need to extend silicon's reach

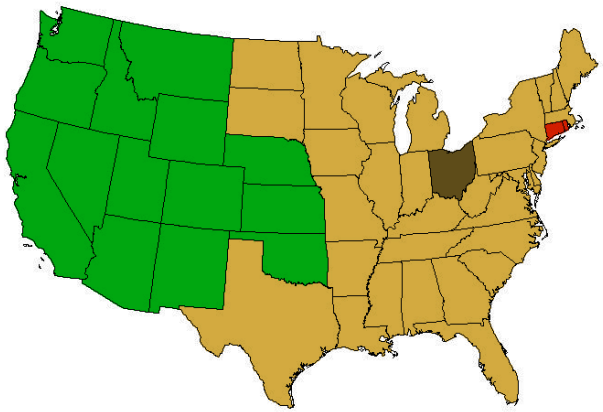


Dopants diffusion governs IR response

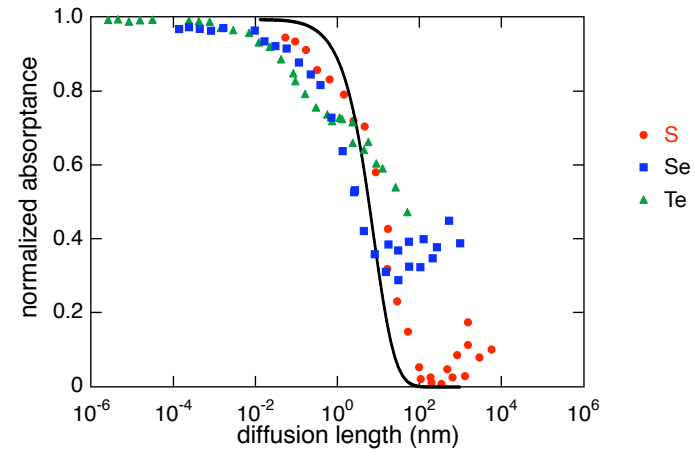


Non-equilibrium doping extends silicon's reach!

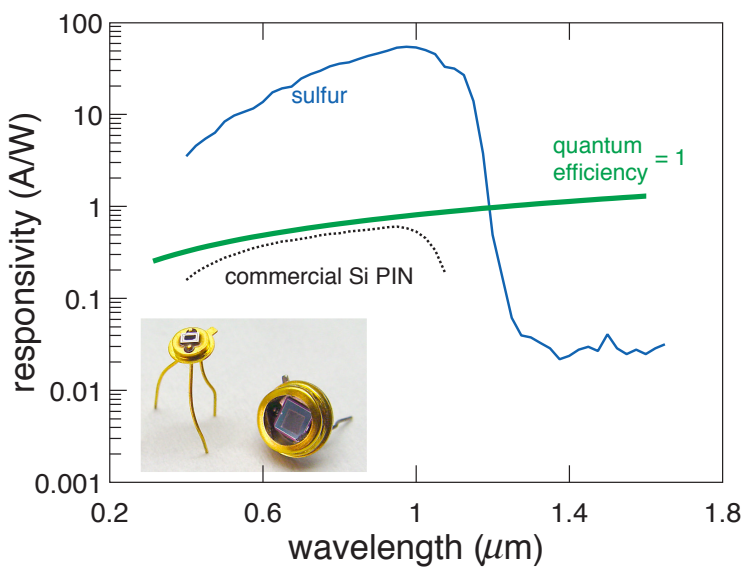
Conclusions



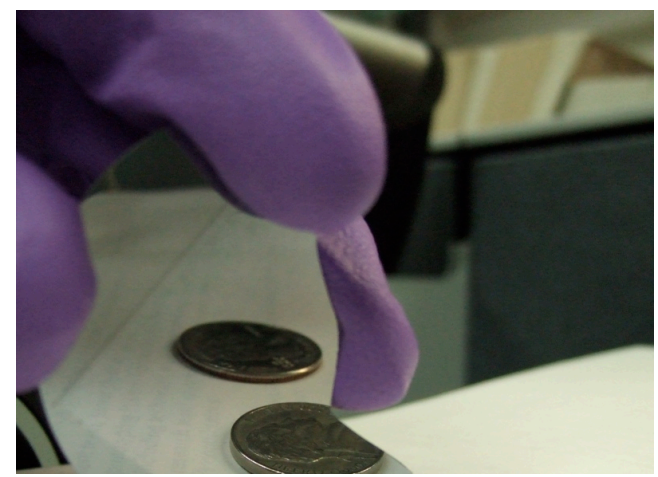
We need to extend silicon's reach



Dopants diffusion governs IR response



Non-equilibrium doping extends silicon's reach!



On our way to solving the puzzle!

Acknowledgements

Eric Diebold, Albert Zhang, Jim Carey, Brian Tull
Mike Aziz, Brion Bob

the Mazur Group

National Science Foundation
Army Research Office

Thanks! Questions?

winkler@physics.harvard.edu

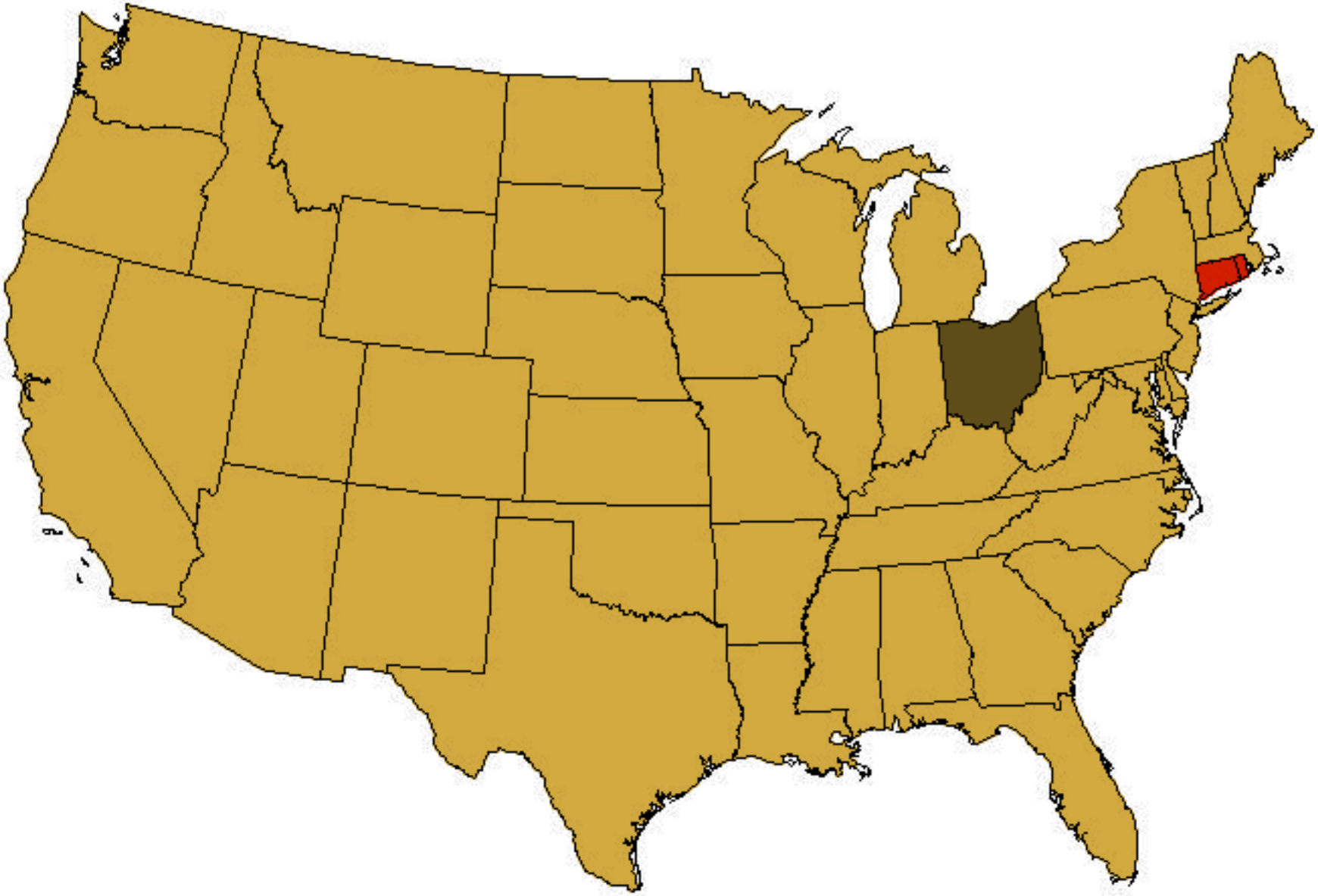
http://mazur-www.harvard.edu

END OF TALK

Why extend silicon's reach?

Why extend silicon's reach?

Why extend silicon's reach?



Engineering silicon?

- a graph showing 1st order calculation of silicon's maximum efficiency
- perhaps a picture of standard silicon cell and a black silicon on glass slide (could show again at the end of the background section)

After writing this talk, i think
the following figures would be useful

1) a graphical representation of how we make the flat surface