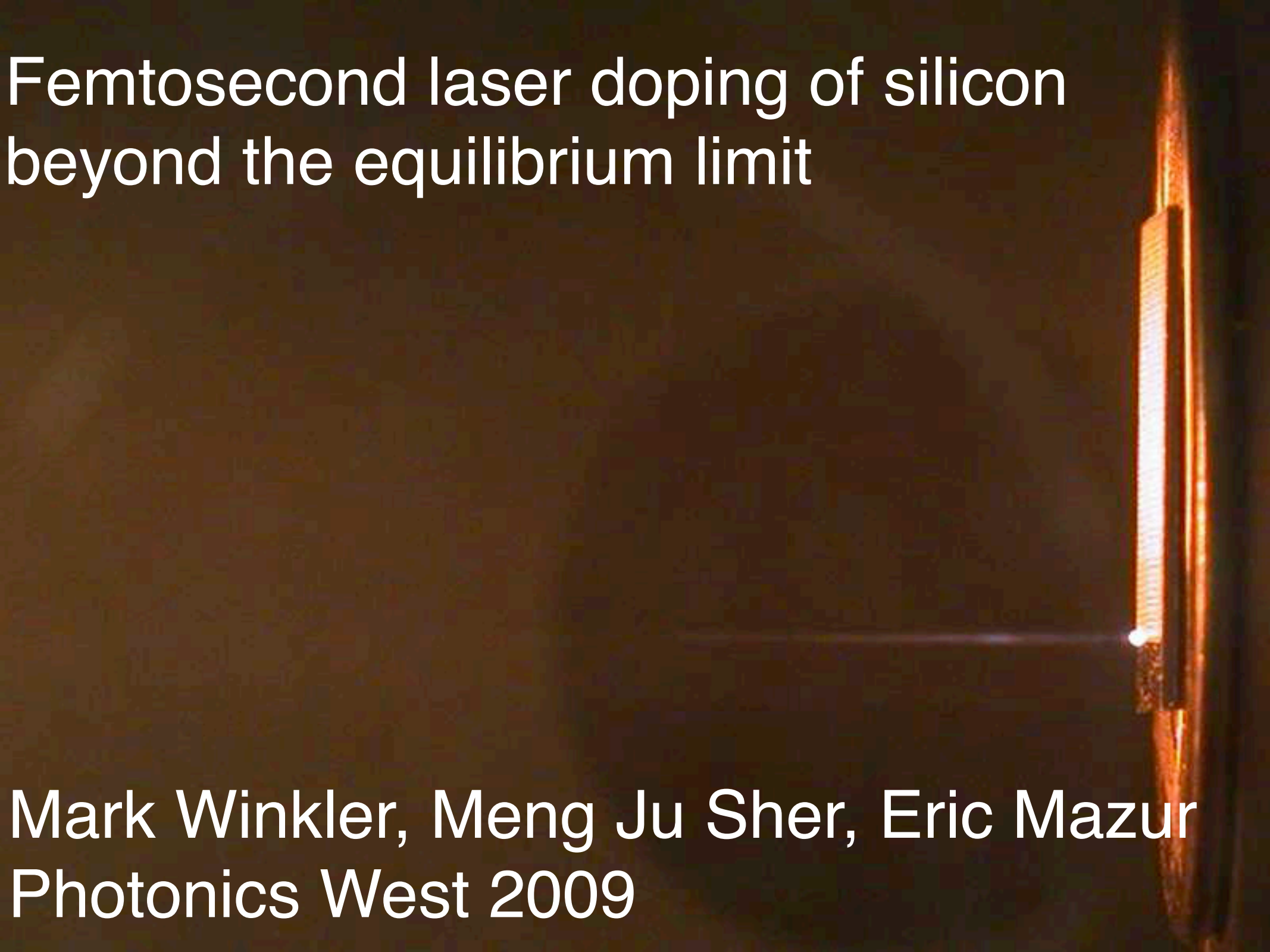
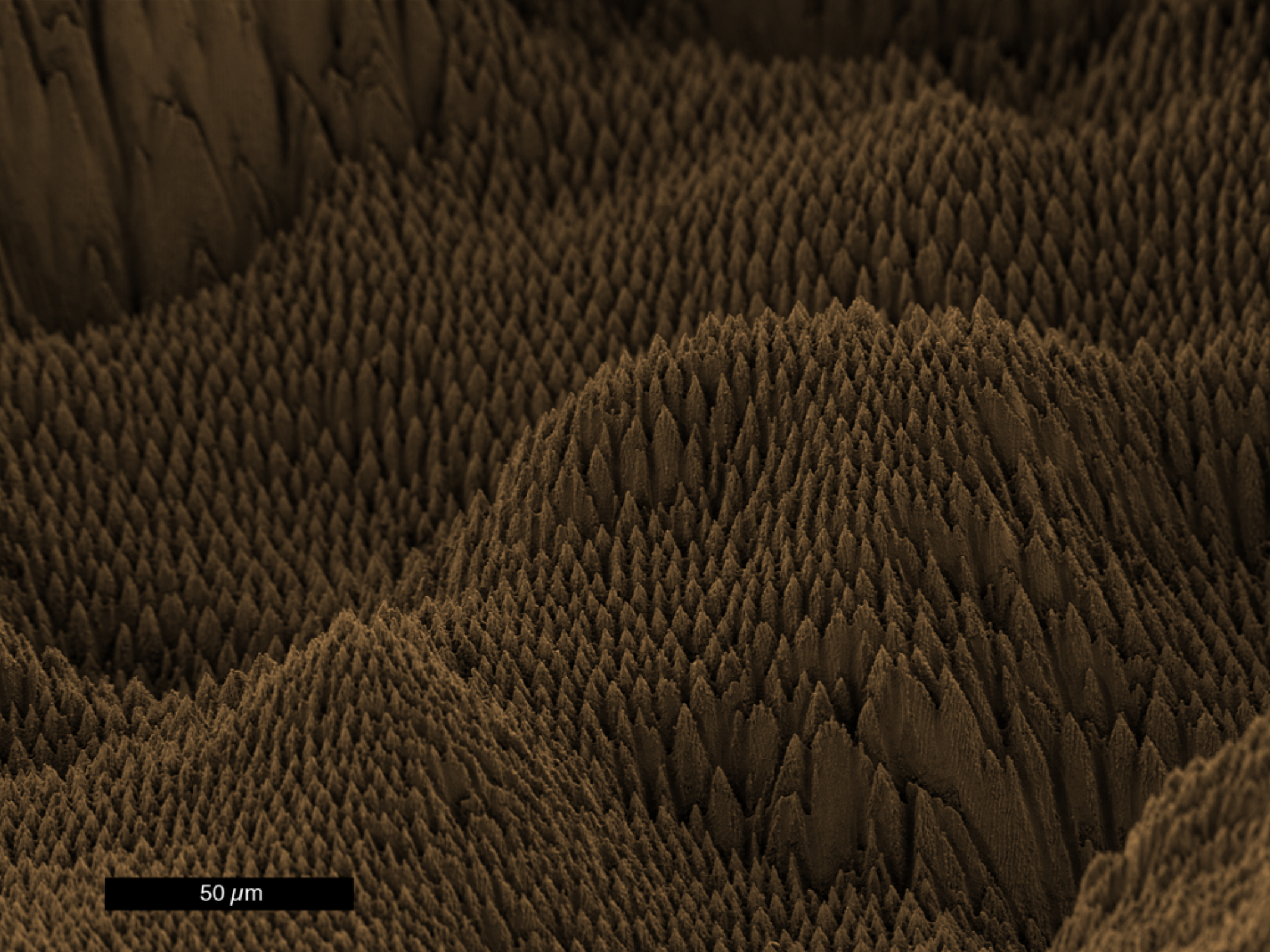
Femtosecond laser doping of silicon beyond the equilibrium limit



Mark Winkler, Meng Ju Sher, Eric Mazur

Photonics West 2009


100 μm


50 μm

Understanding non-equilibrium doping:

Understanding non-equilibrium doping:

- Laser doping – how we do it and what we know

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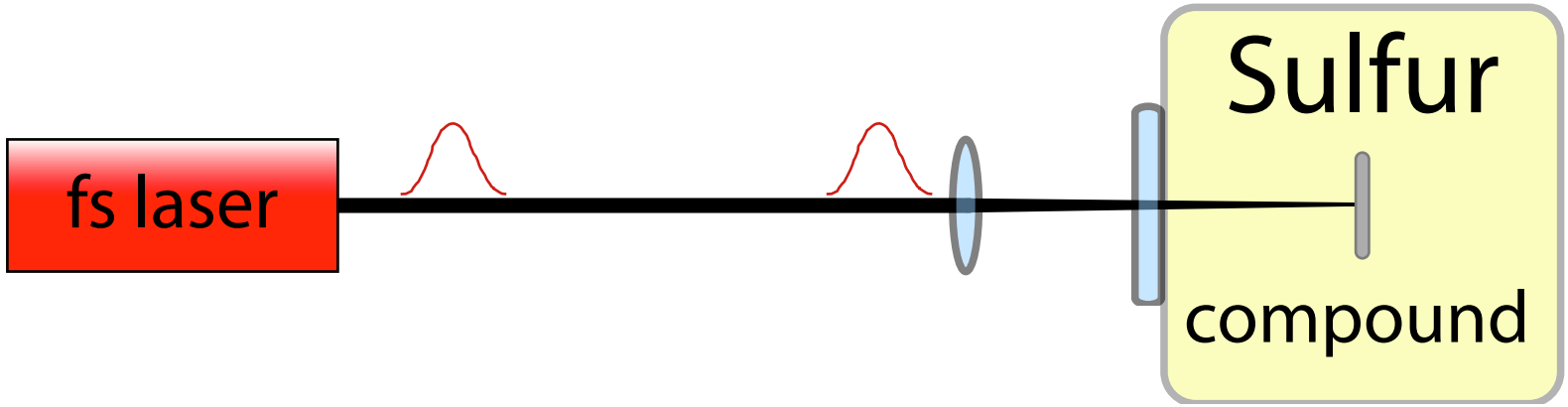
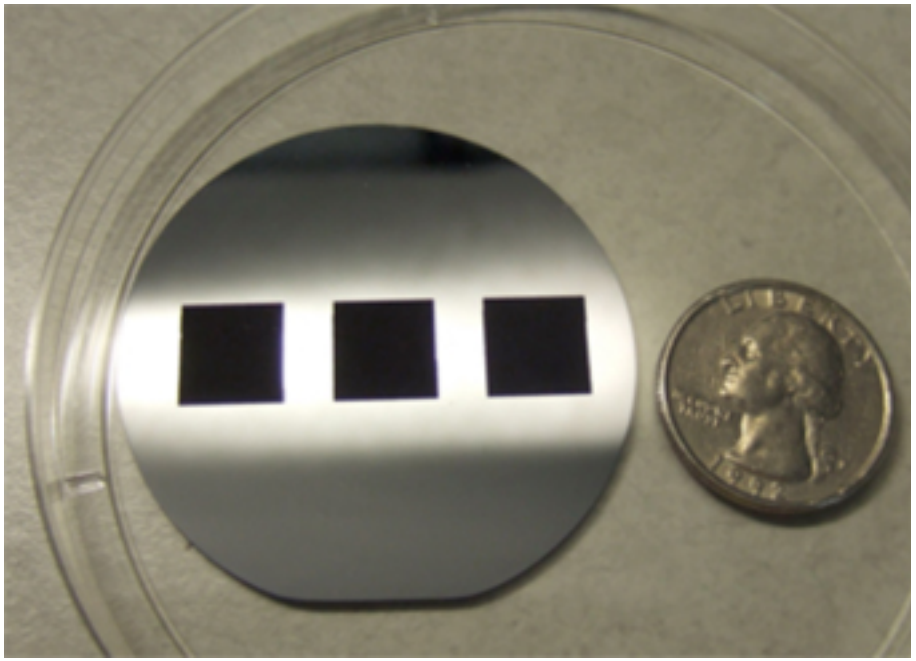
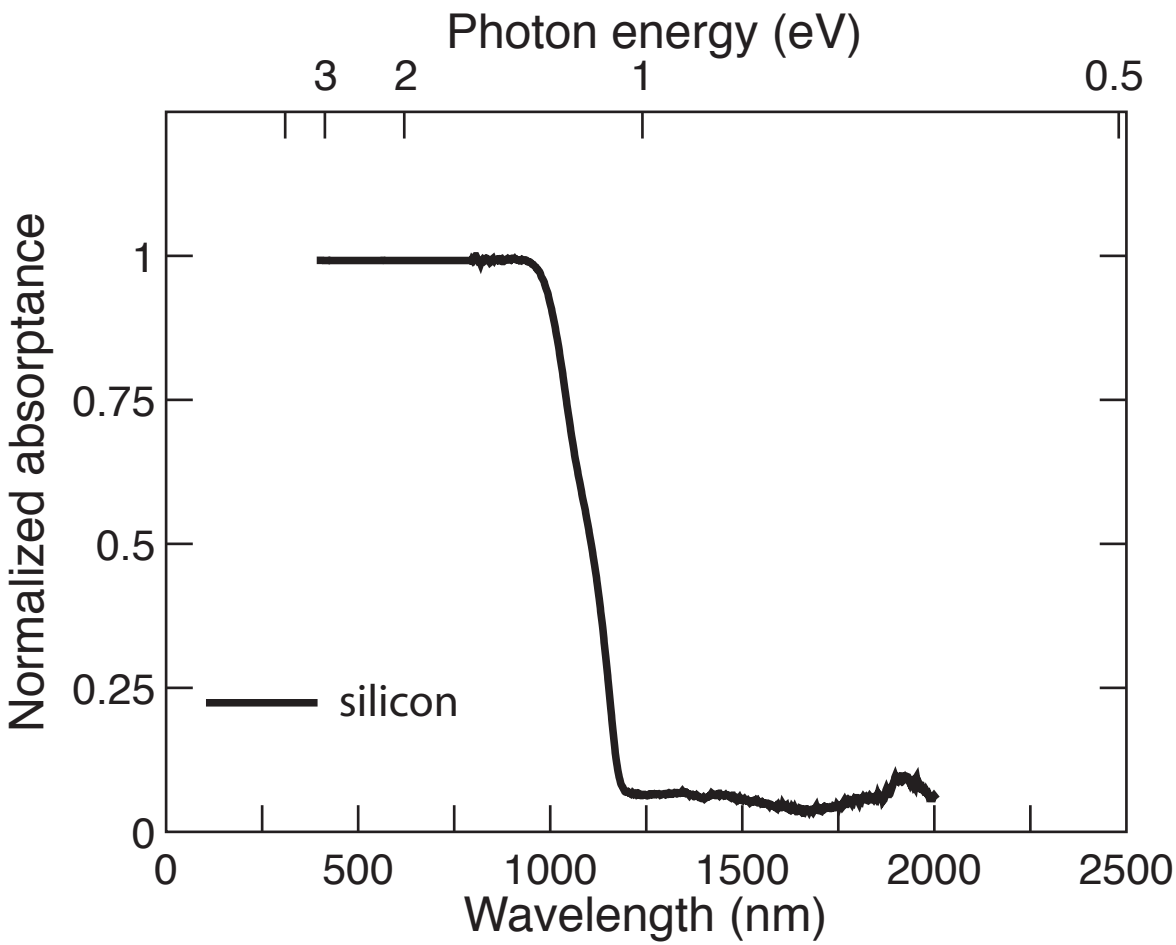
- Laser doping – how we do it and what we know
- Non-equilibrium dopant concentrations
- Hall measurements – determining dopant energetics

femtosecond laser doped silicon

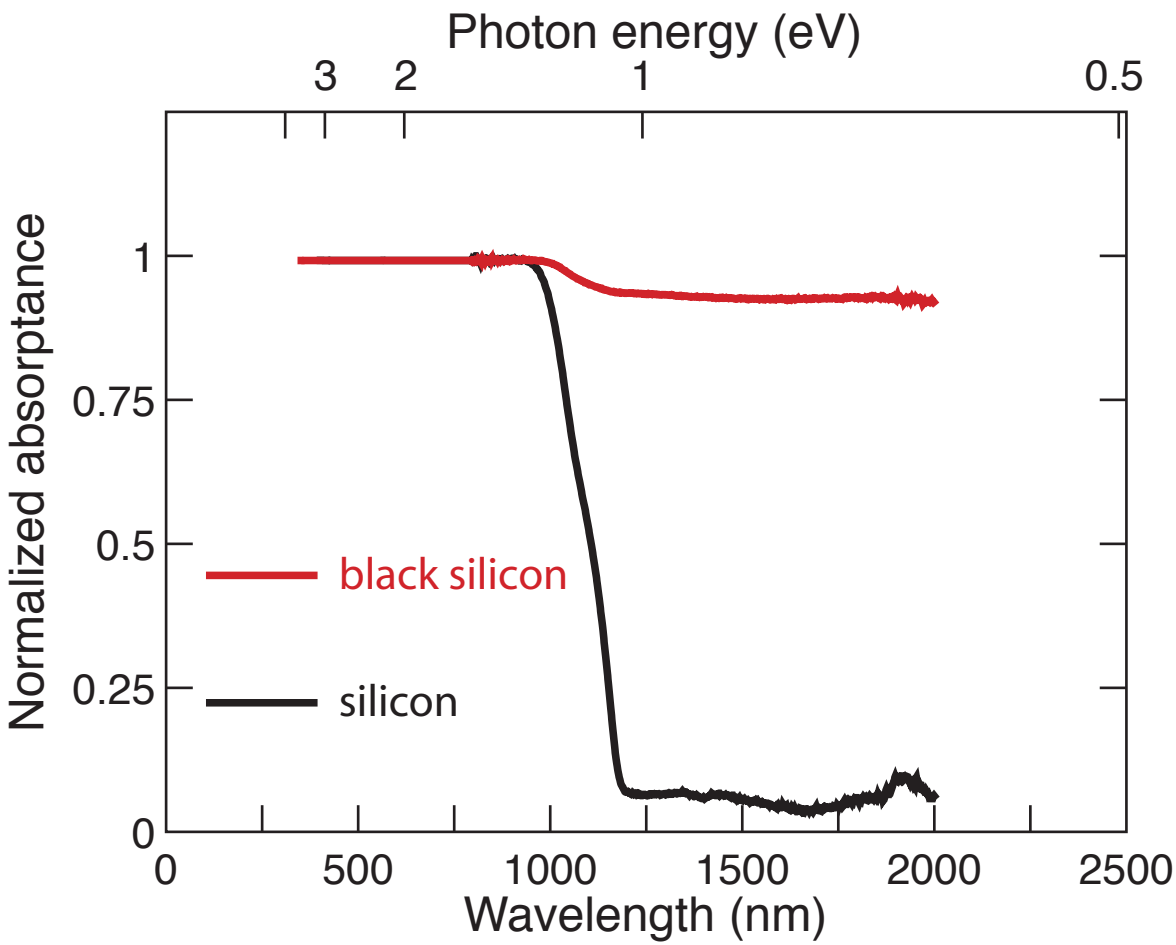




$$\overline{A} = \frac{1-R-T}{1-R}$$



$$\overline{A} = \frac{1-R-T}{1-R}$$



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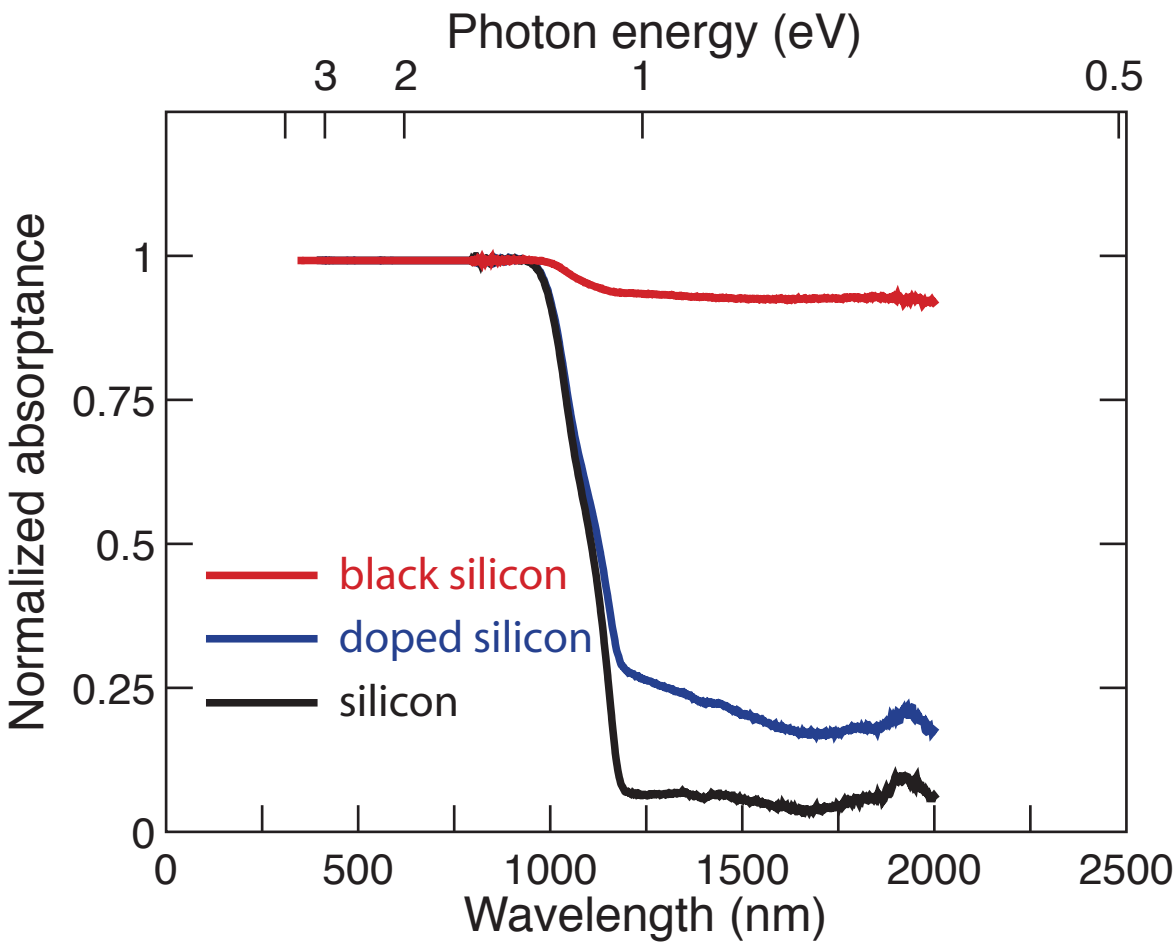
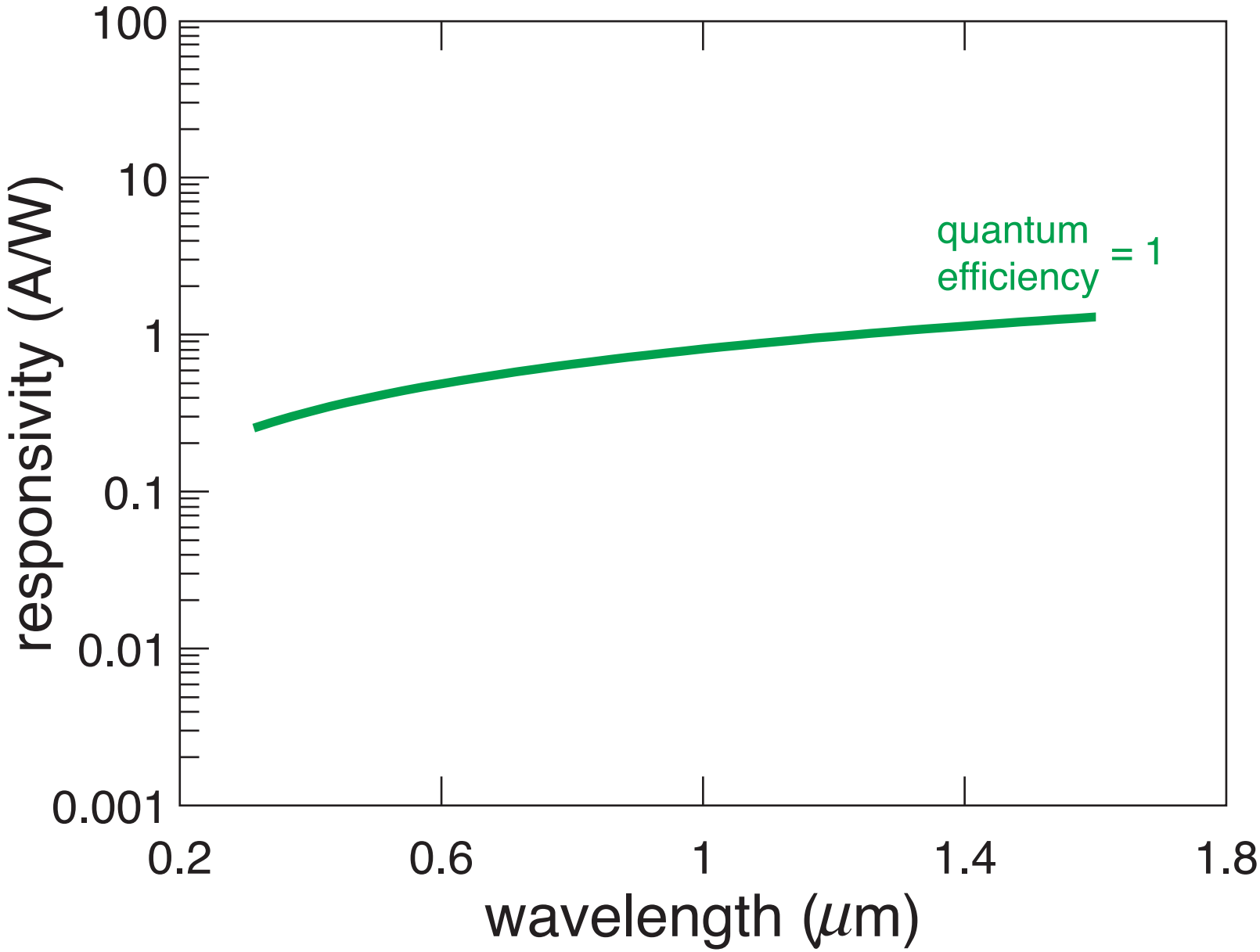


Laser-doping yields interesting optoelectronic devices



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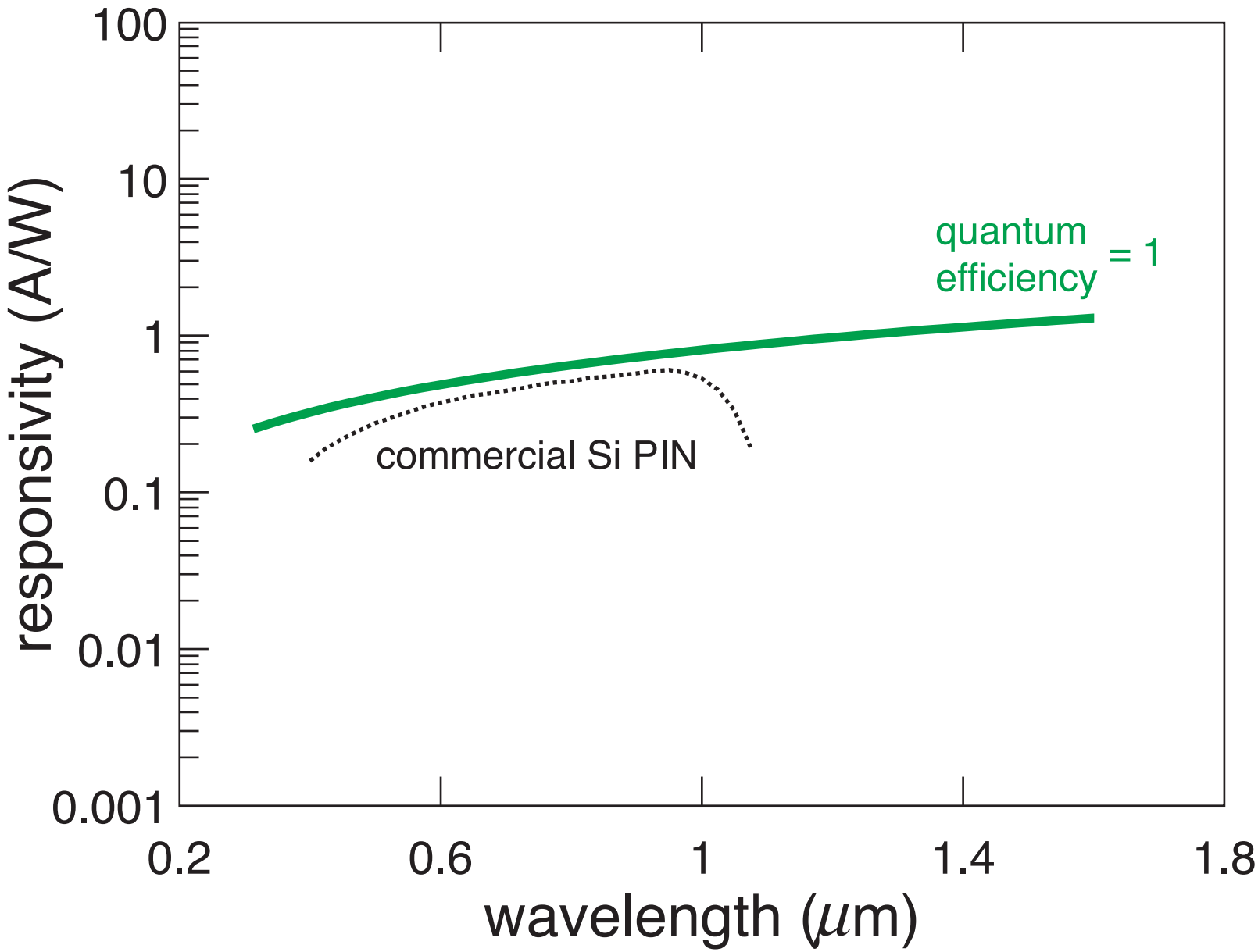

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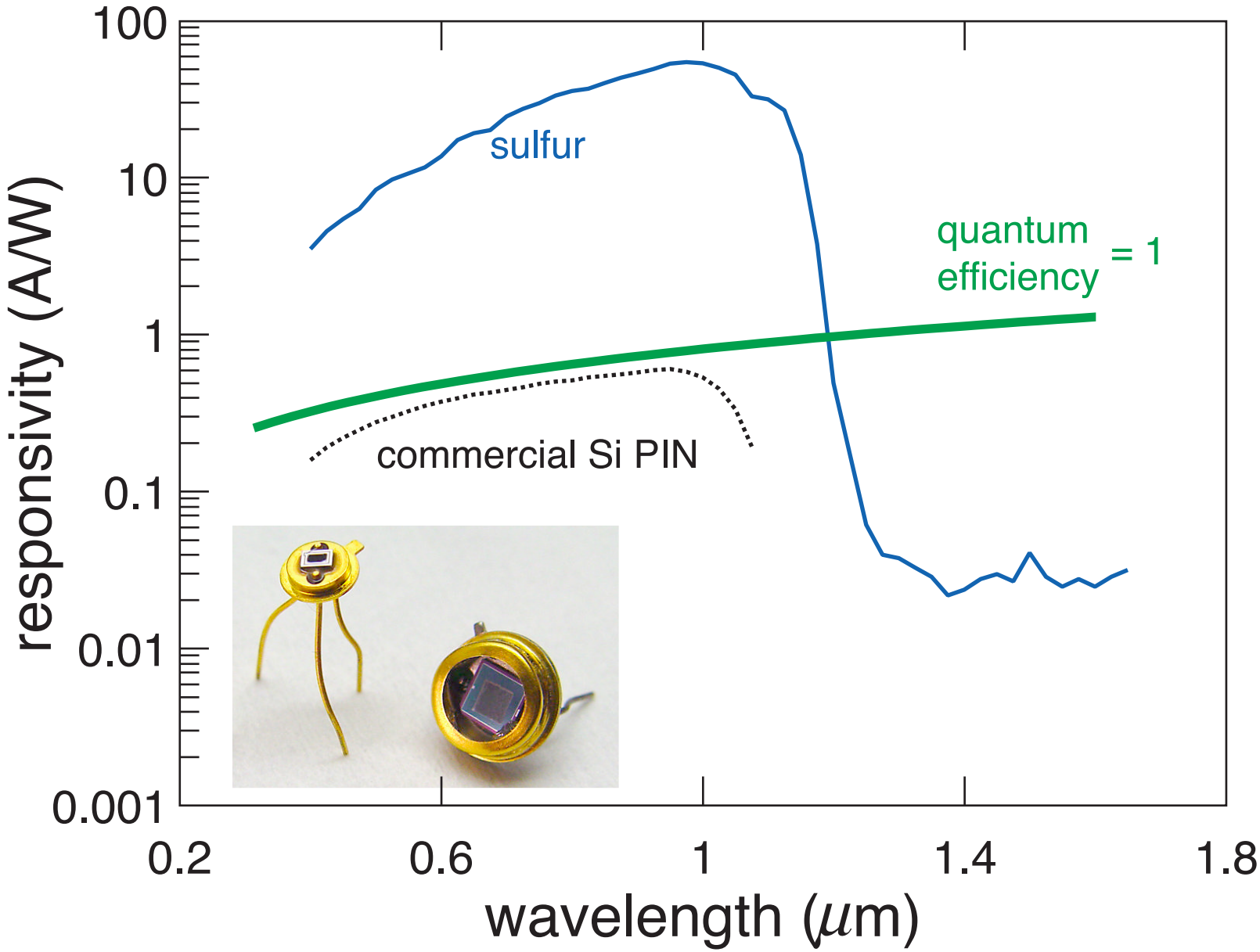
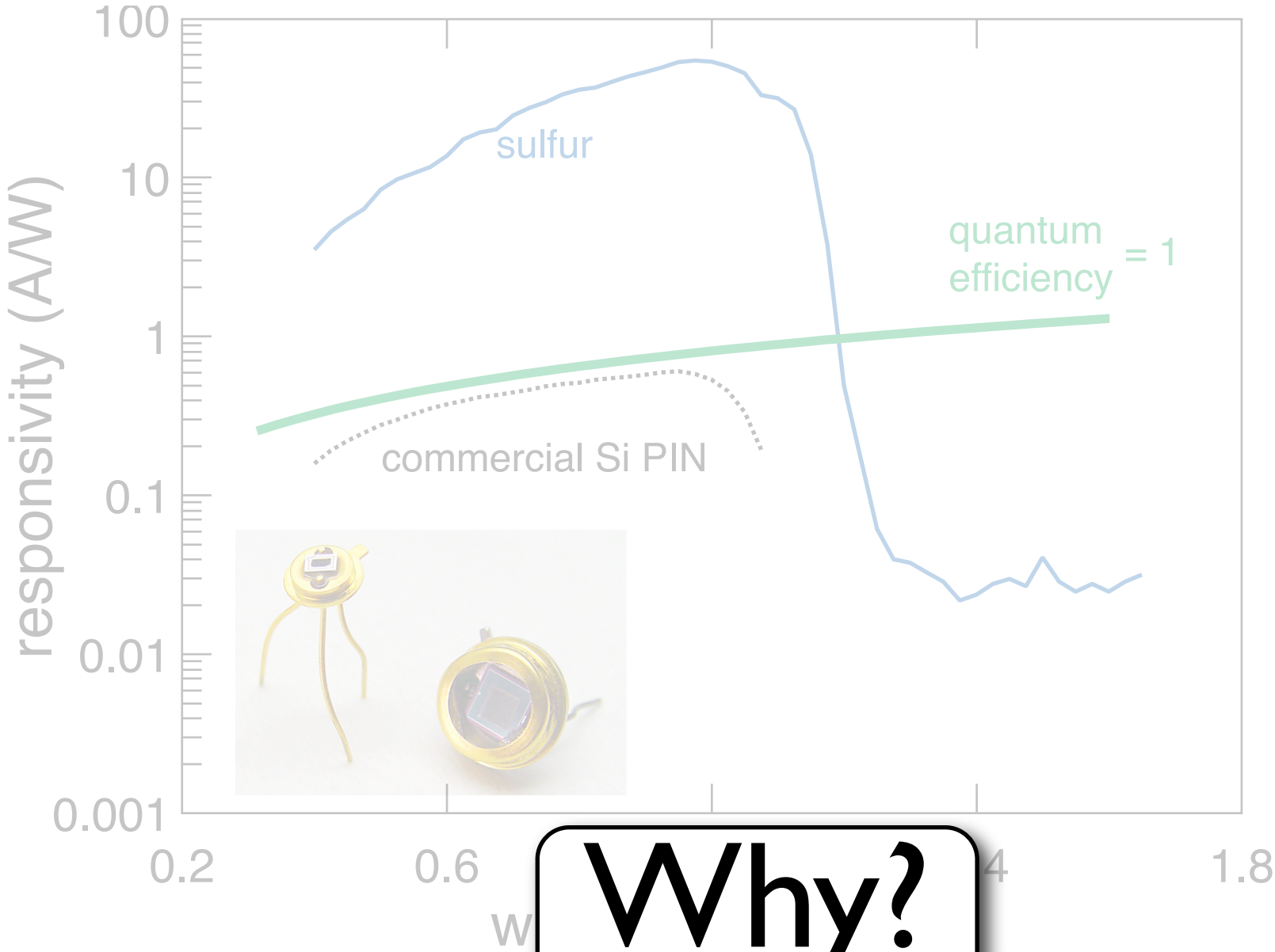
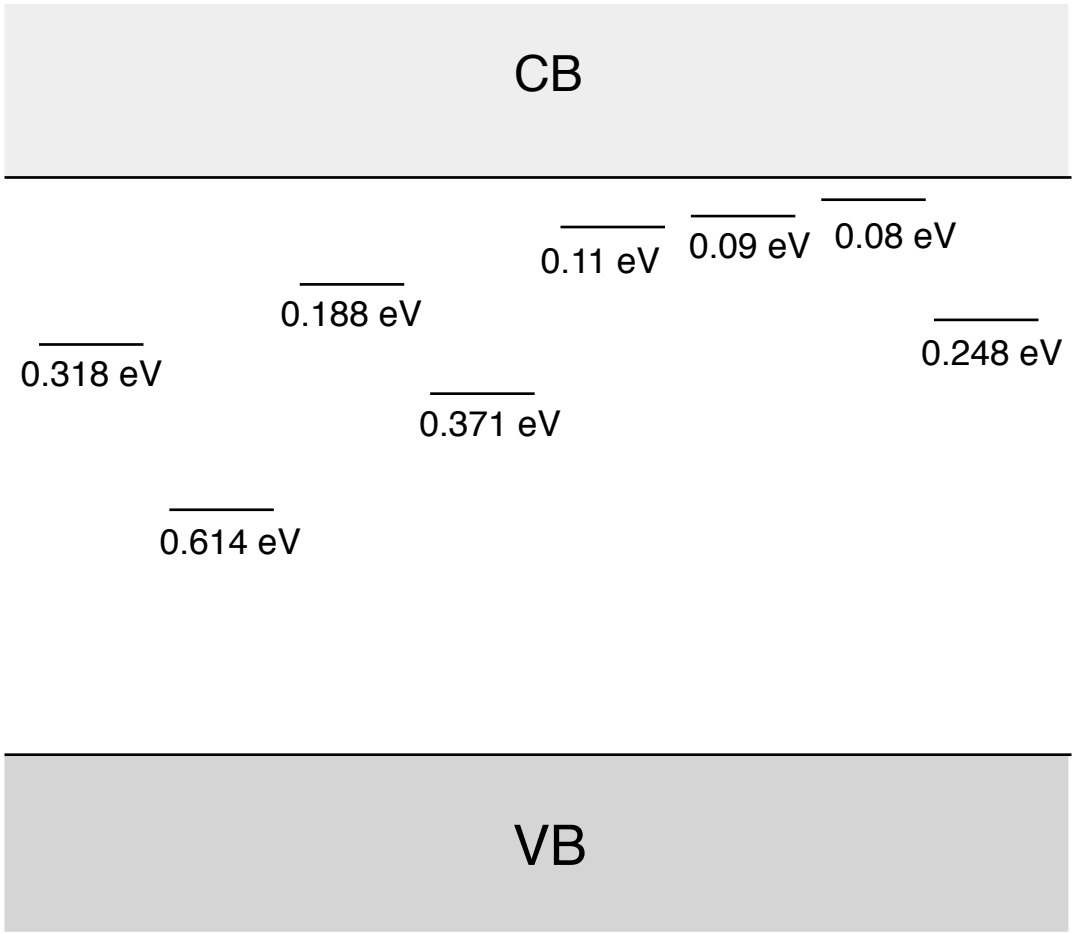


Laser-doping yields interesting optoelectronic devices

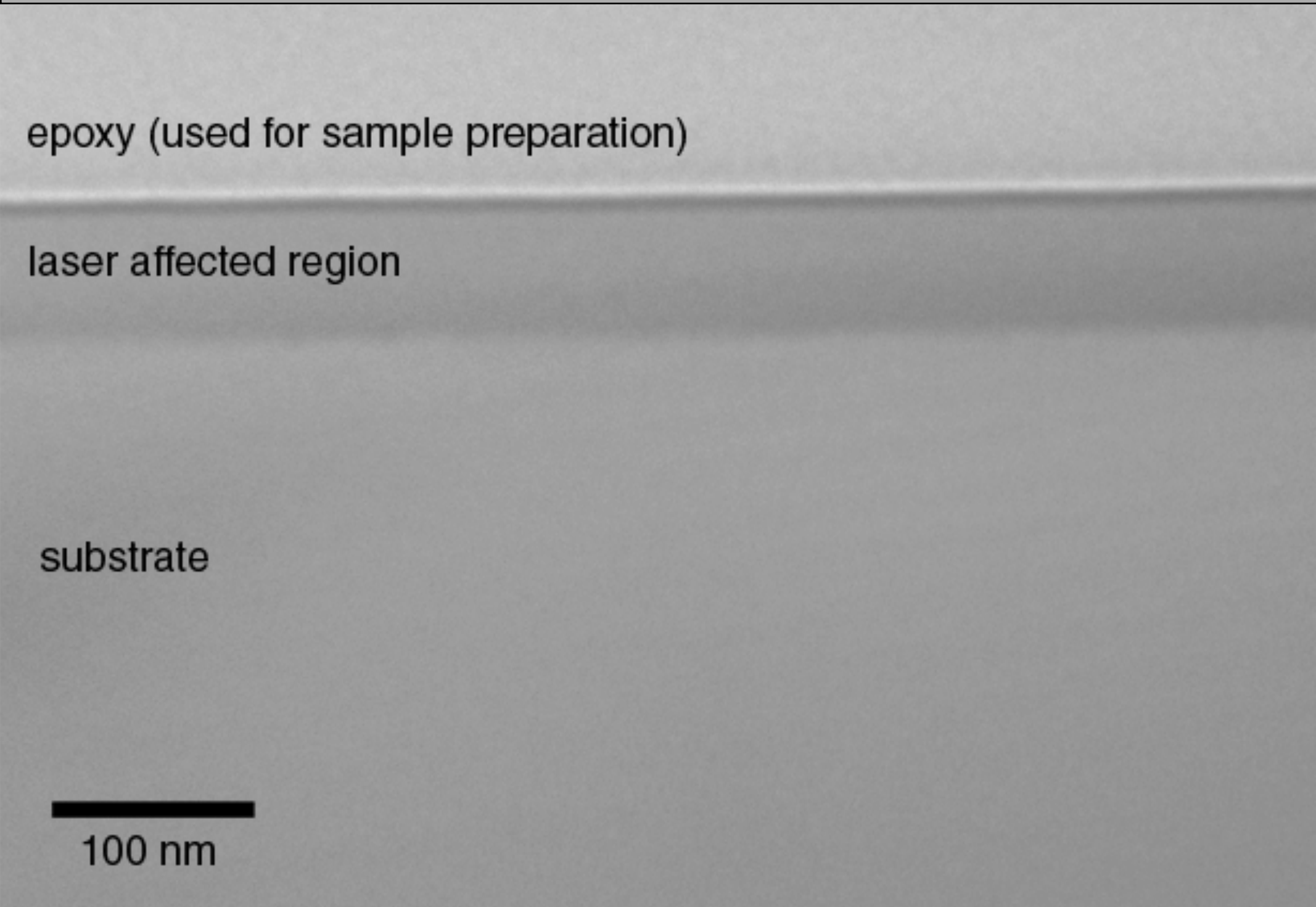


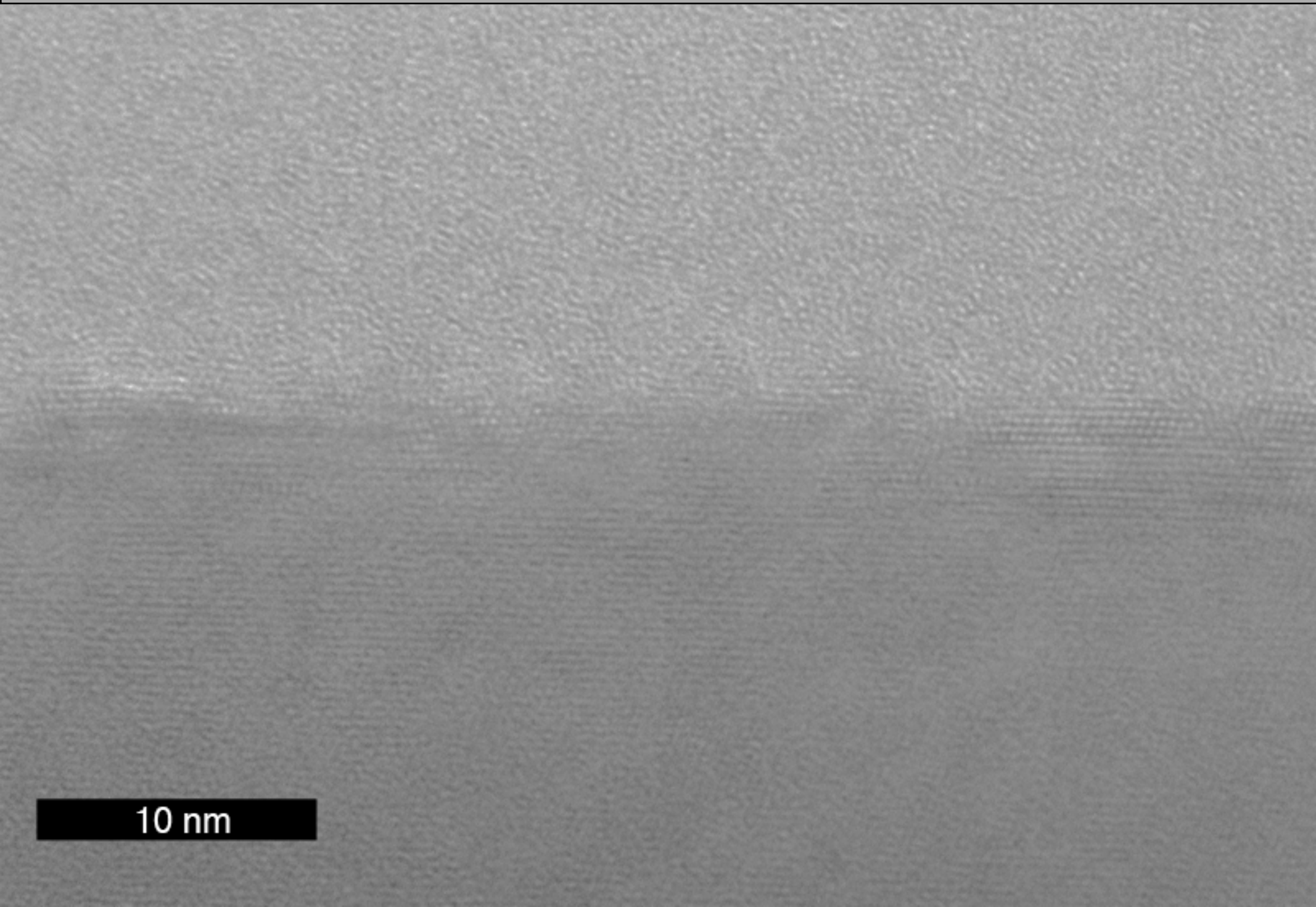
Why?



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

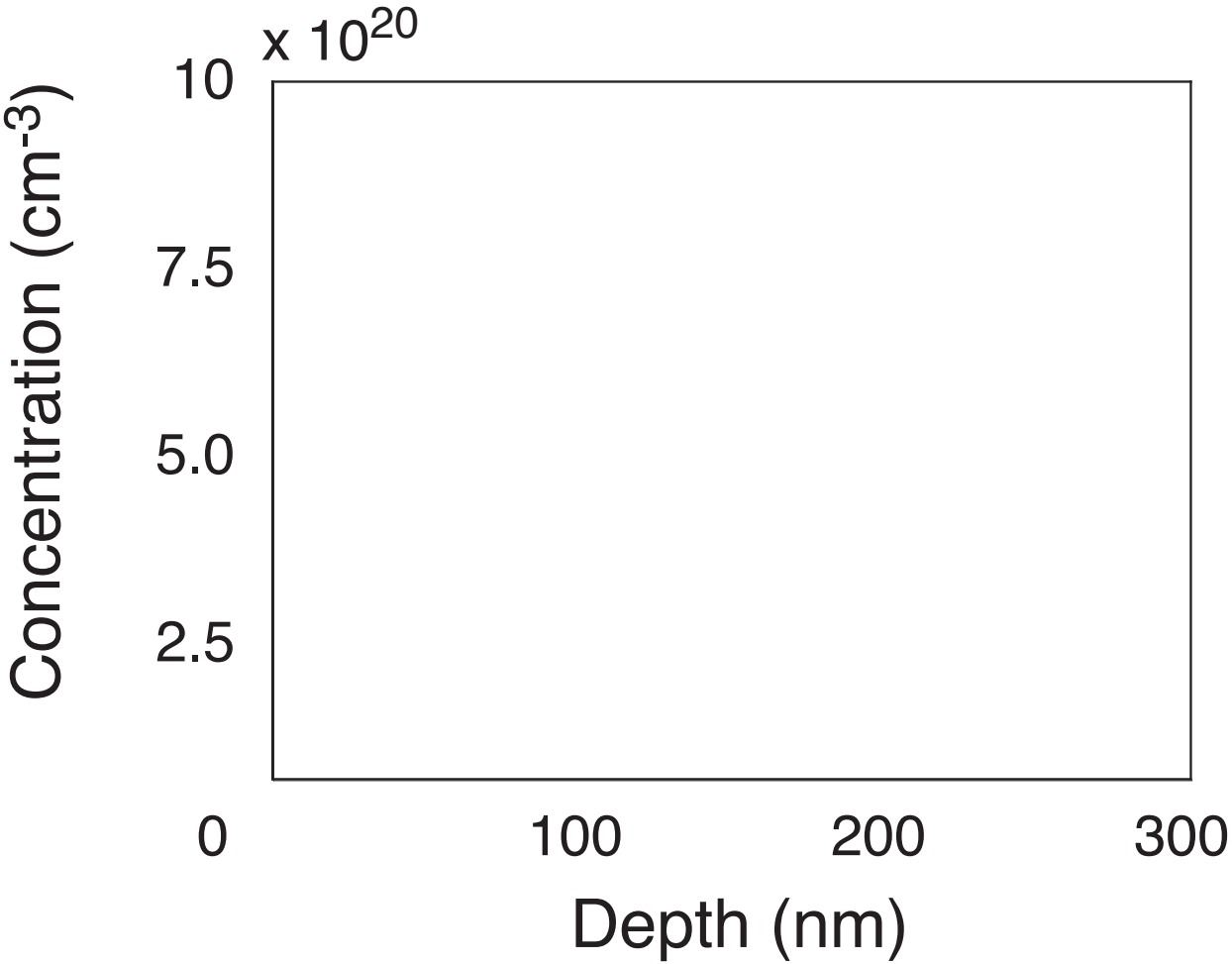
Hypothesis: non-equilibrium doping yields impurity band


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


10 nm

fs lasers dope beyond equilibrium limit

secondary ion mass spectroscopy (SIMS)



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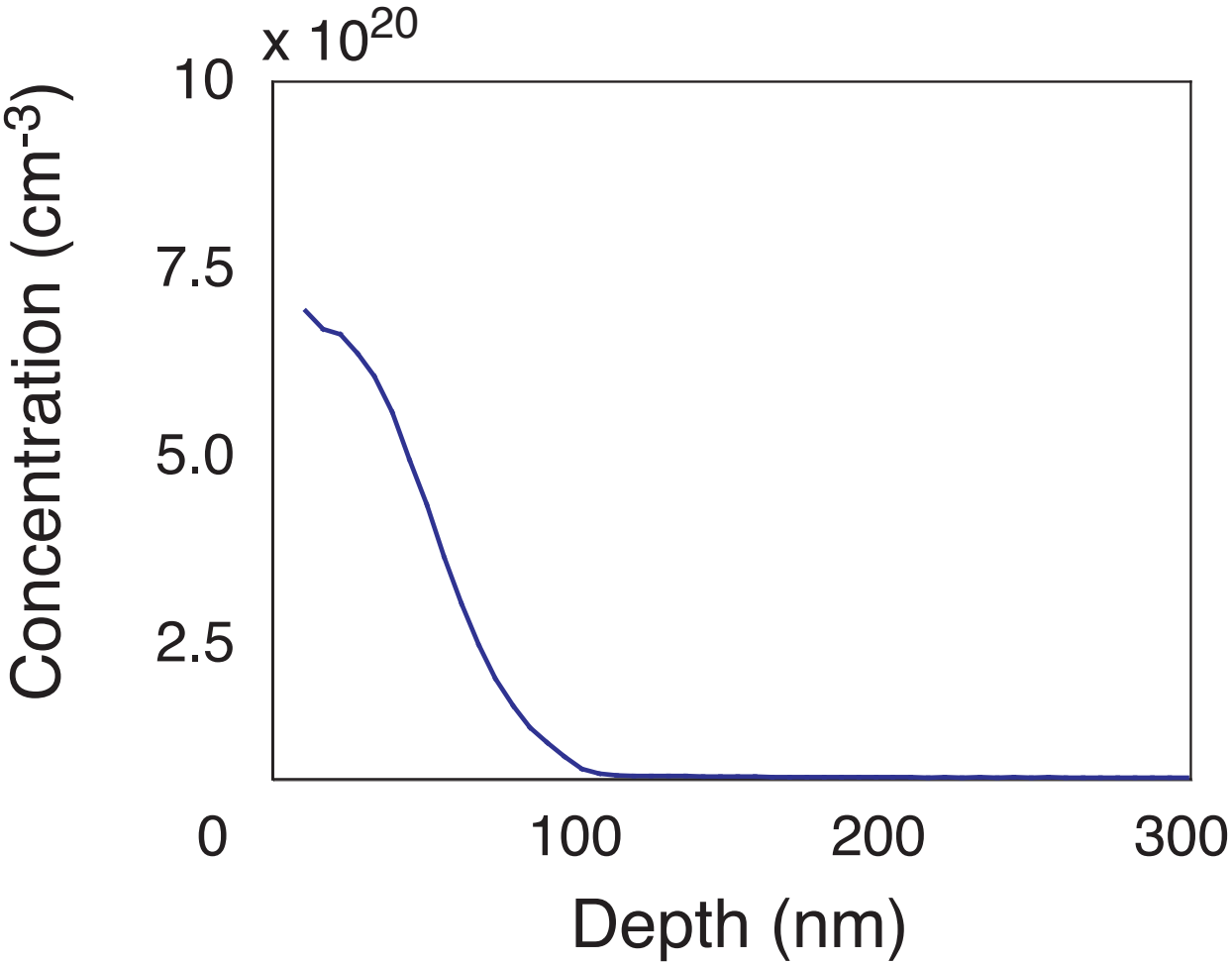

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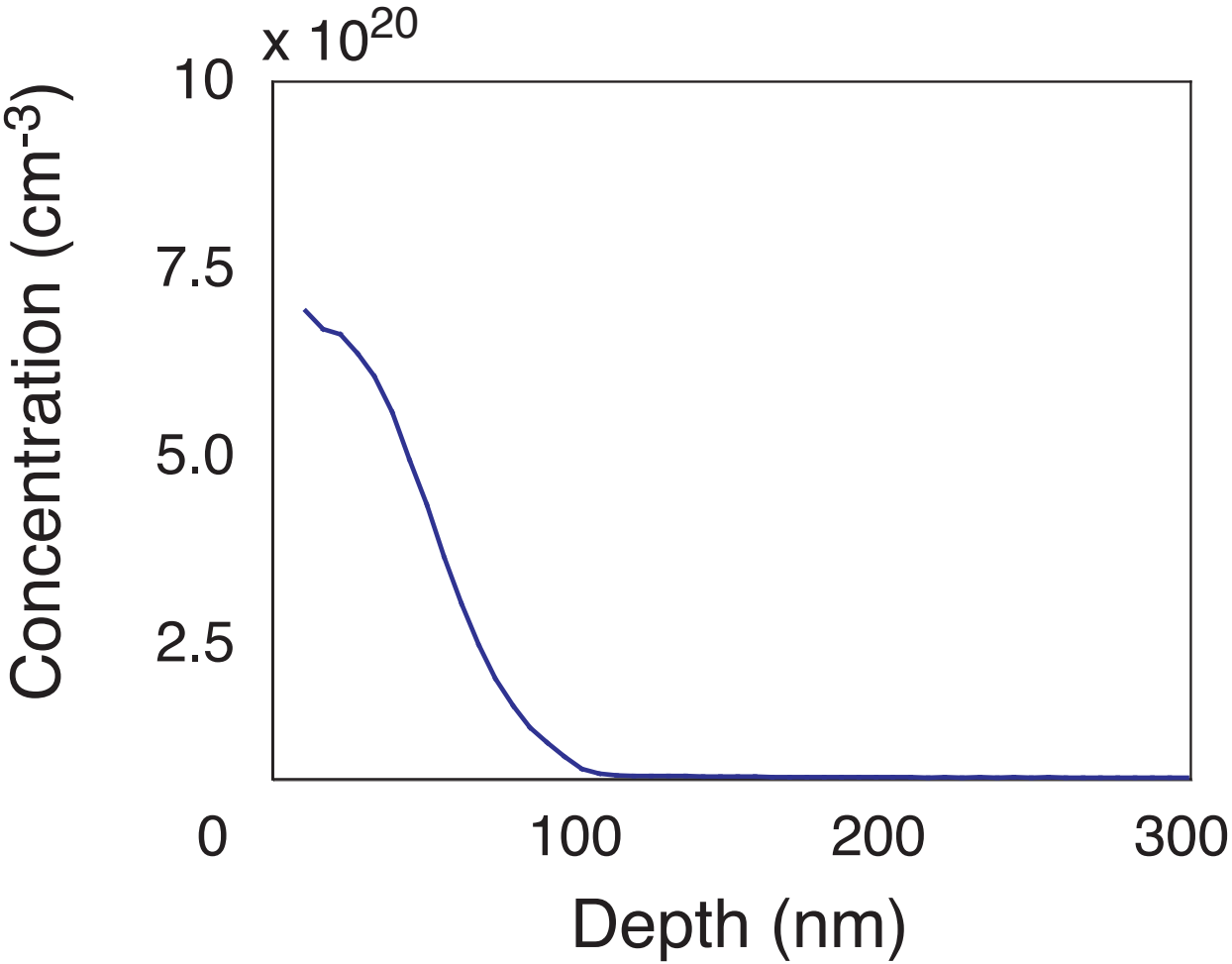

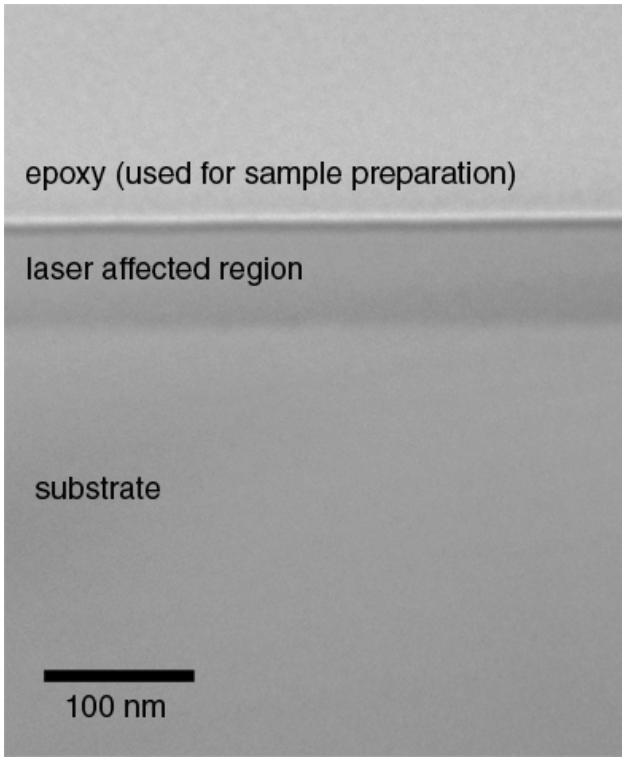

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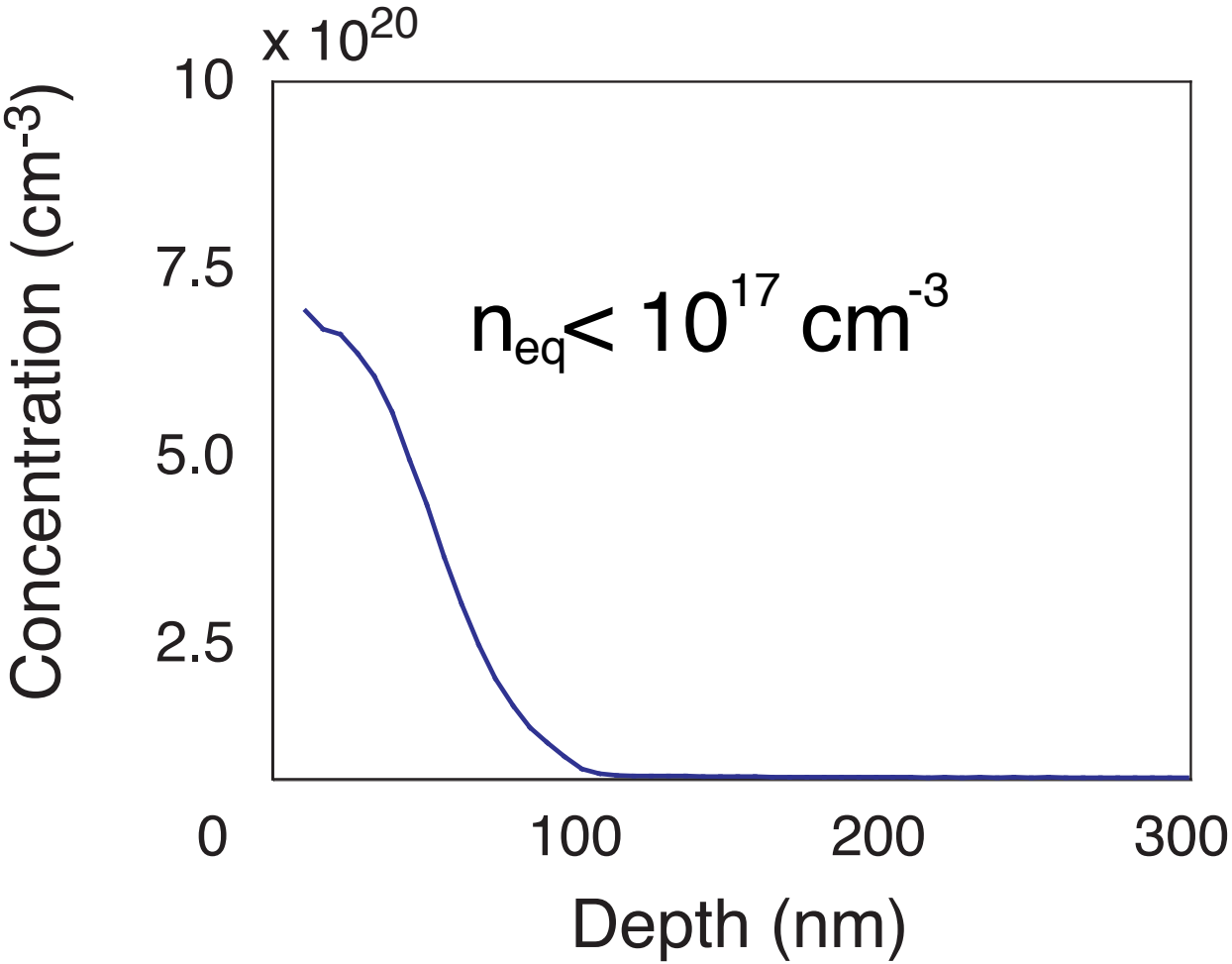

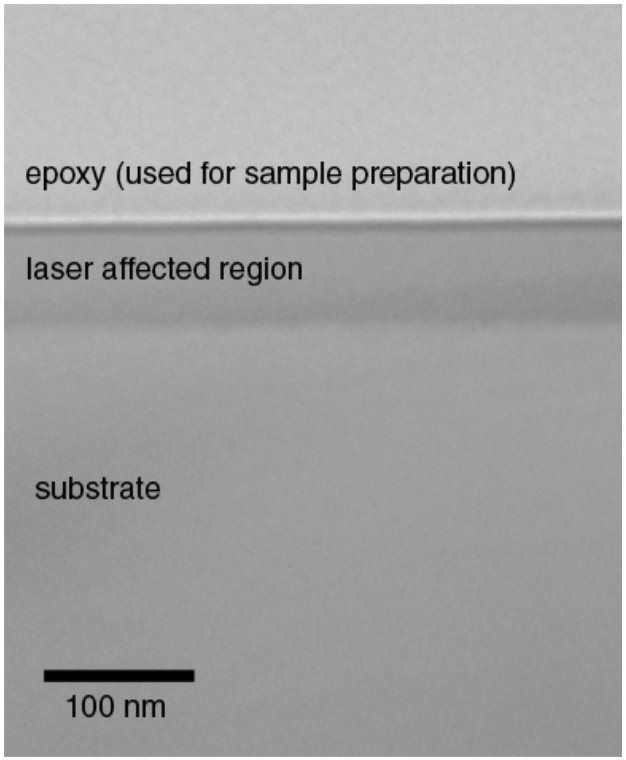

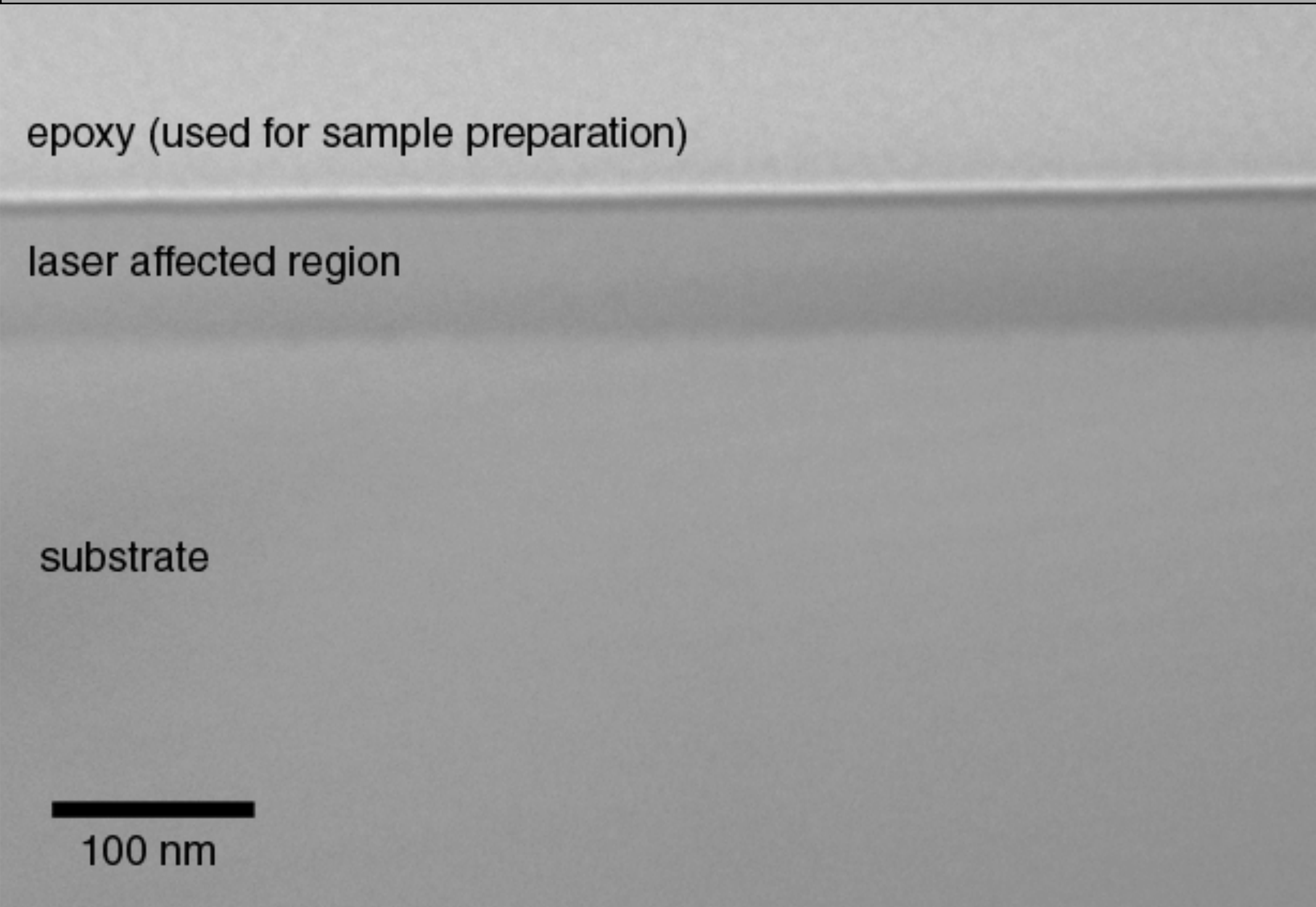
epoxy (used for sample preparation)
laser affected region
substrate
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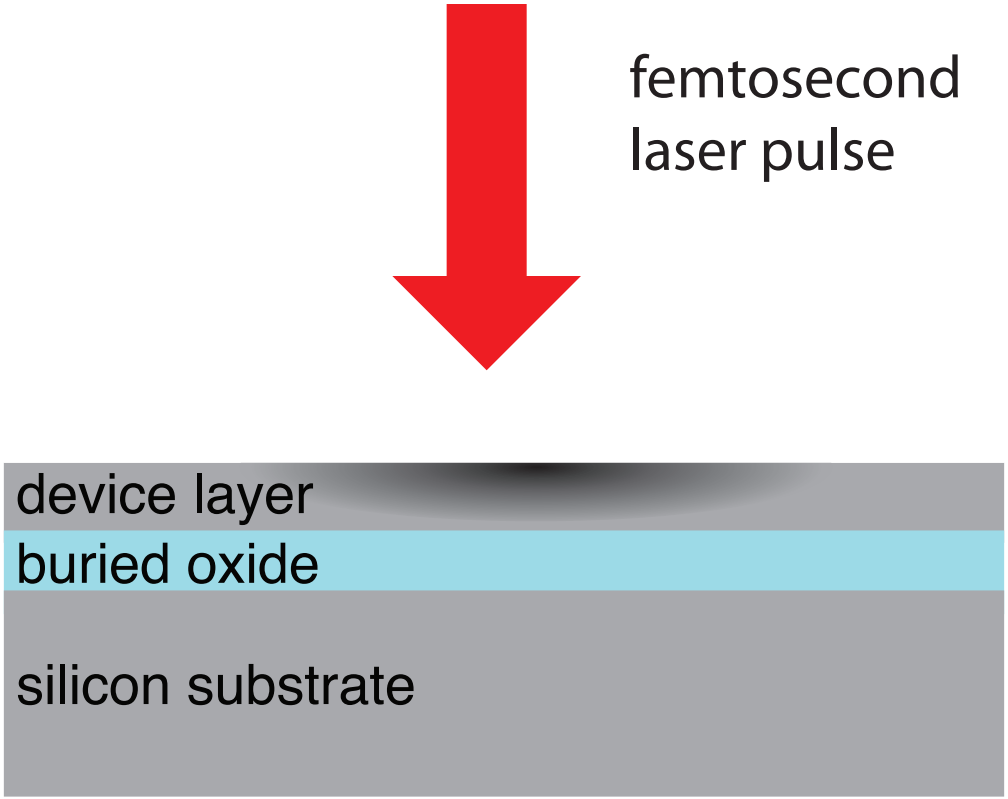
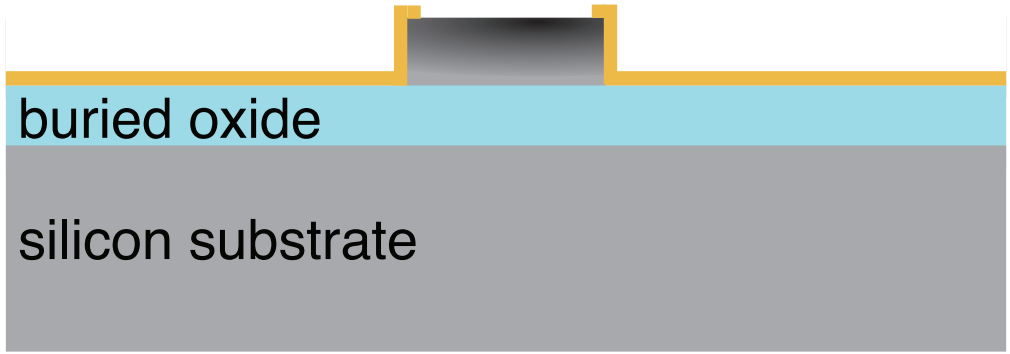
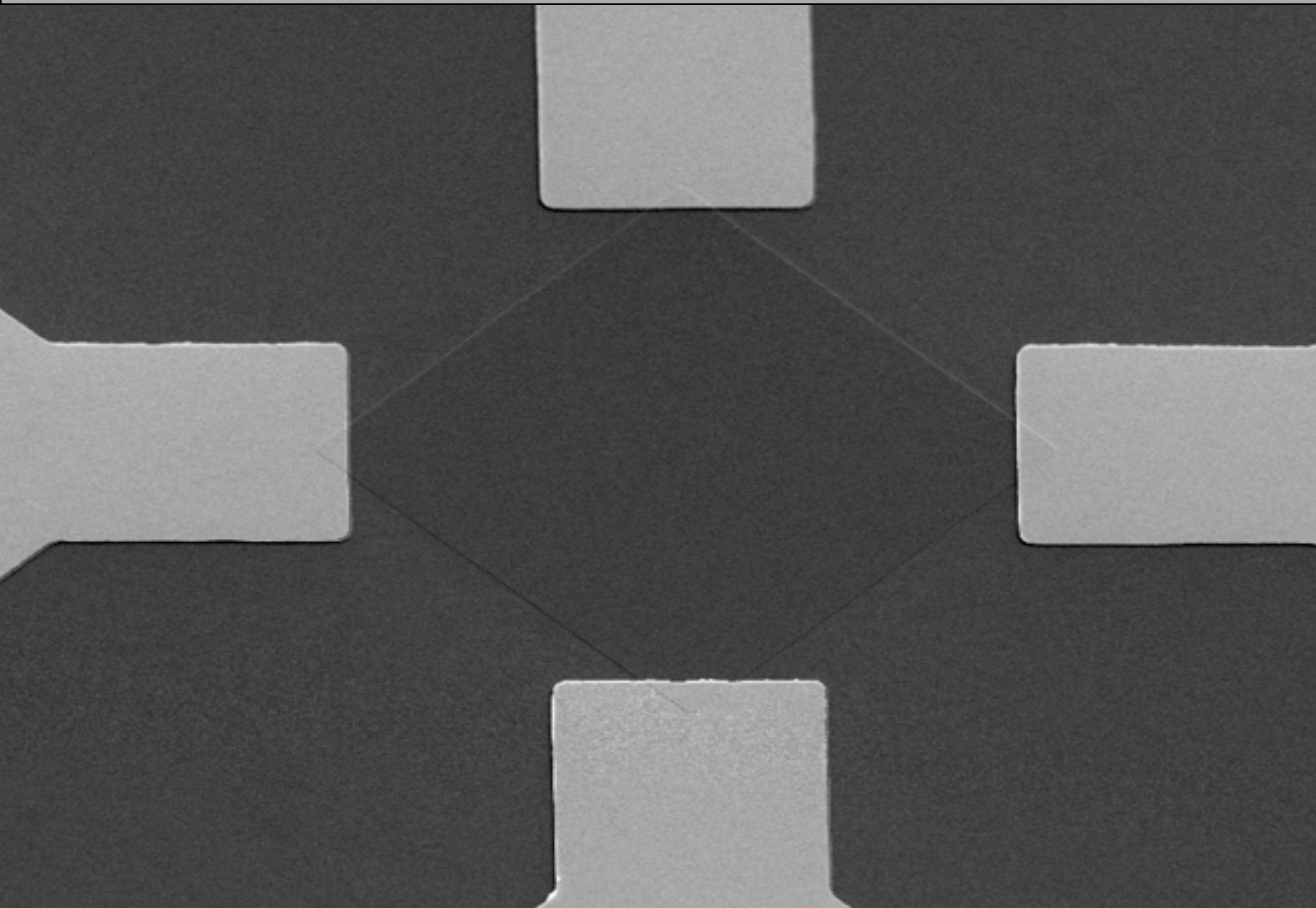
Isolate surface properties

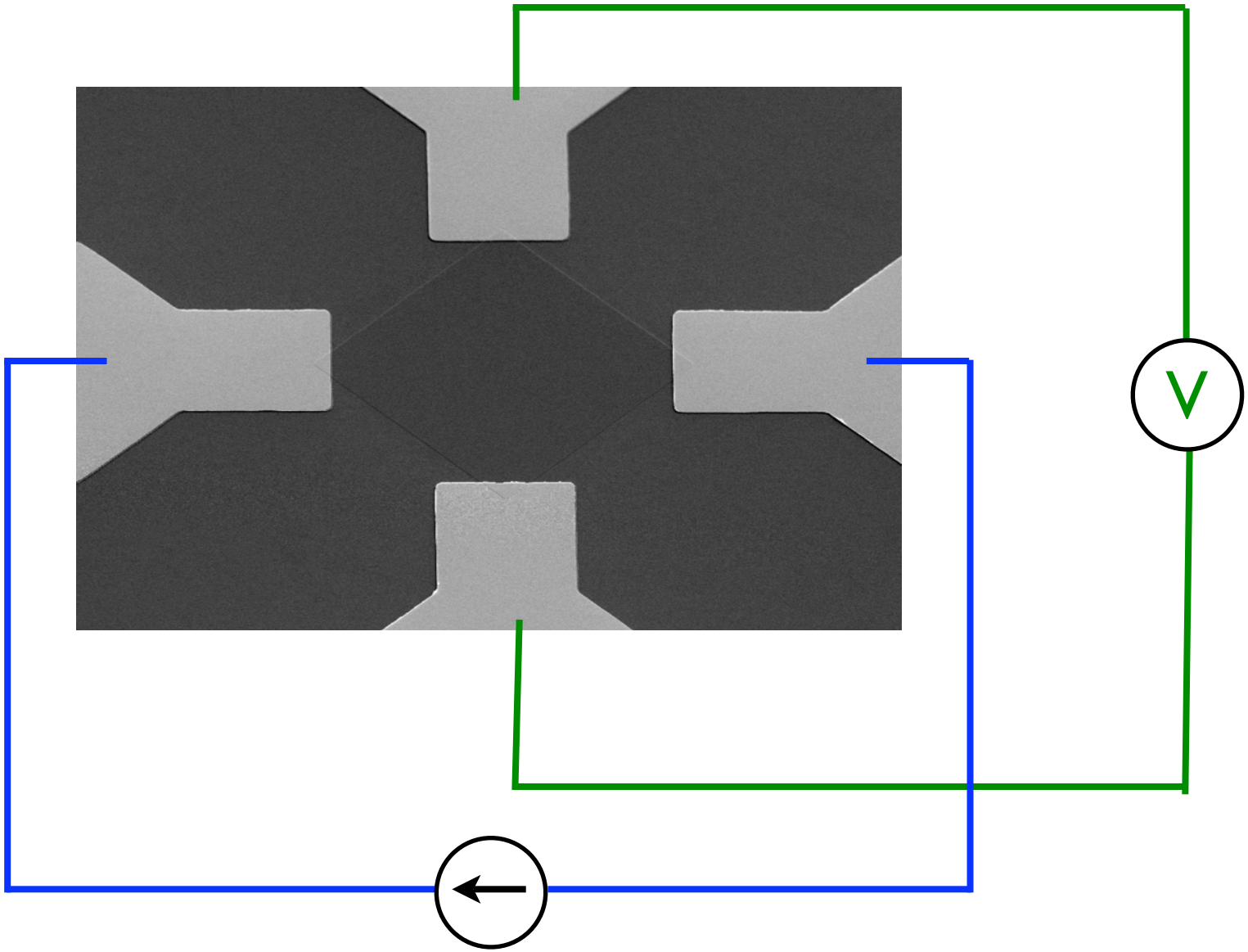
Isolate surface properties



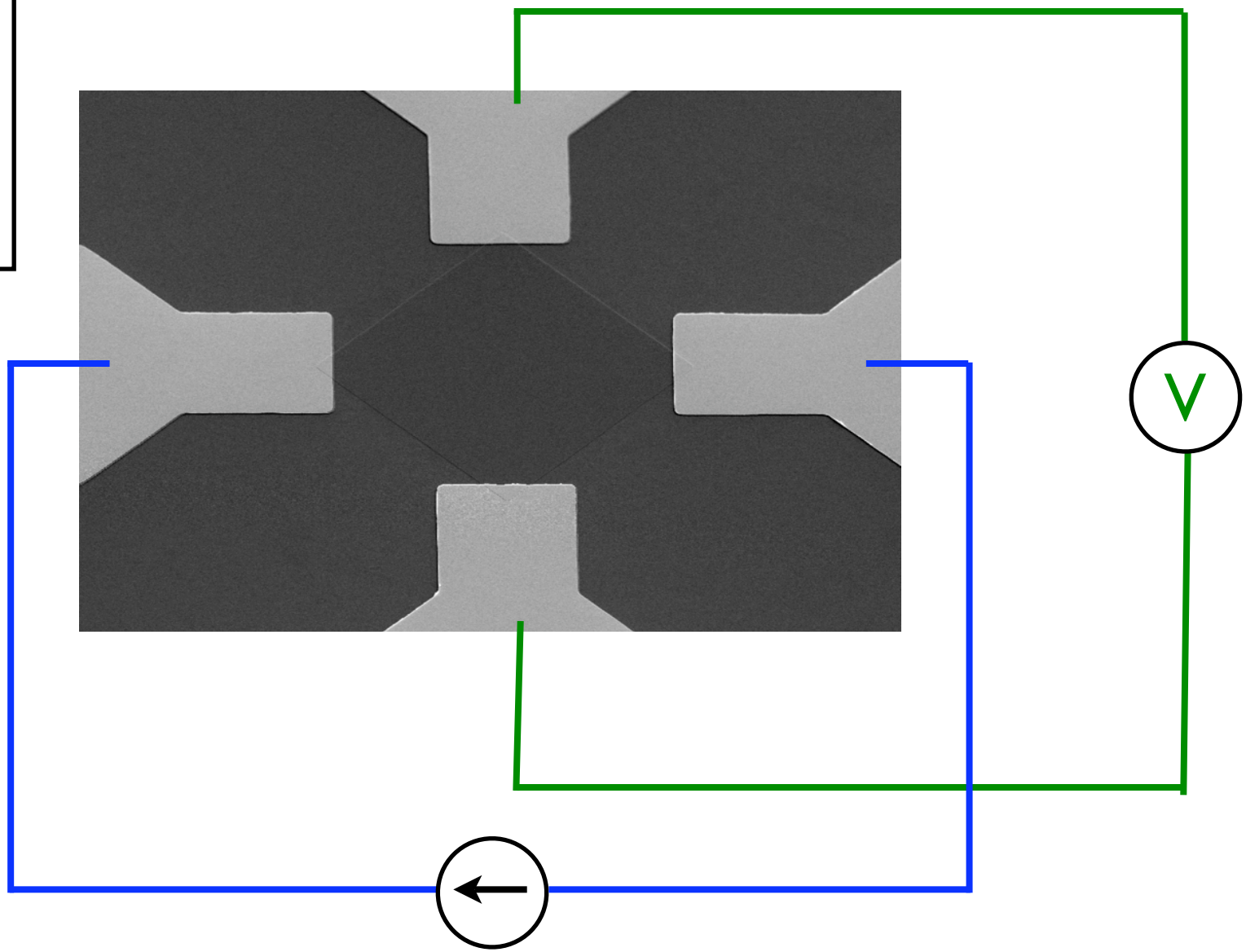
Isolate surface properties





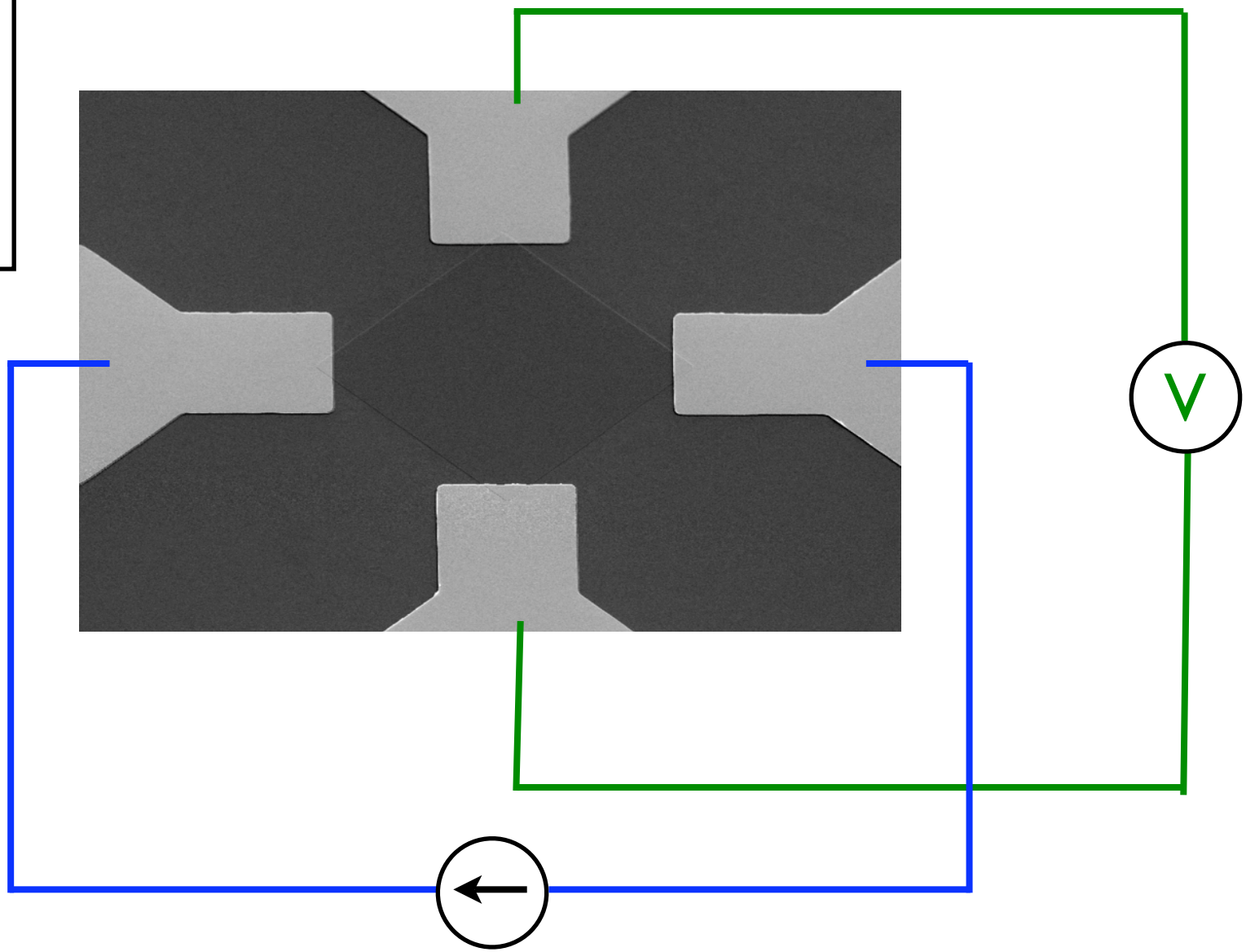

V

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

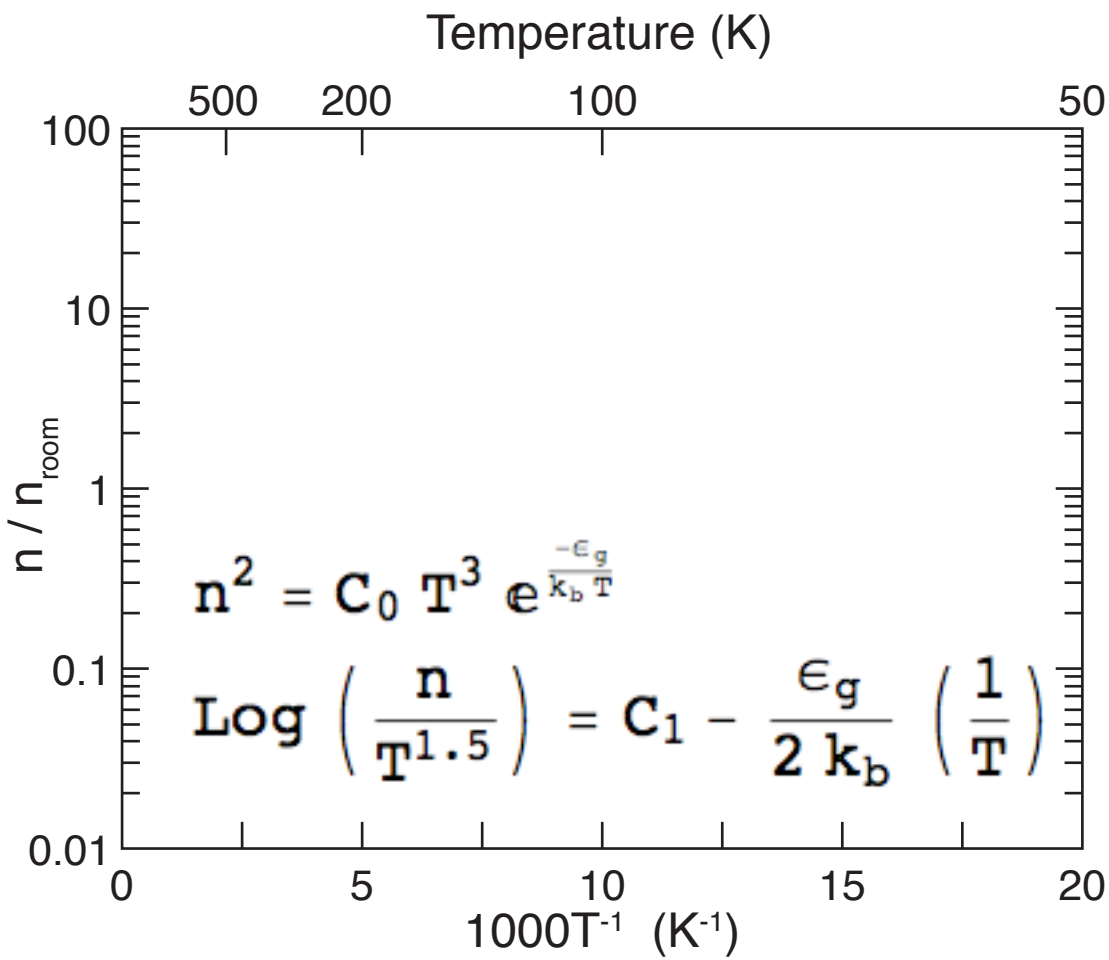


$$n = \frac{IB}{qdV}$$

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

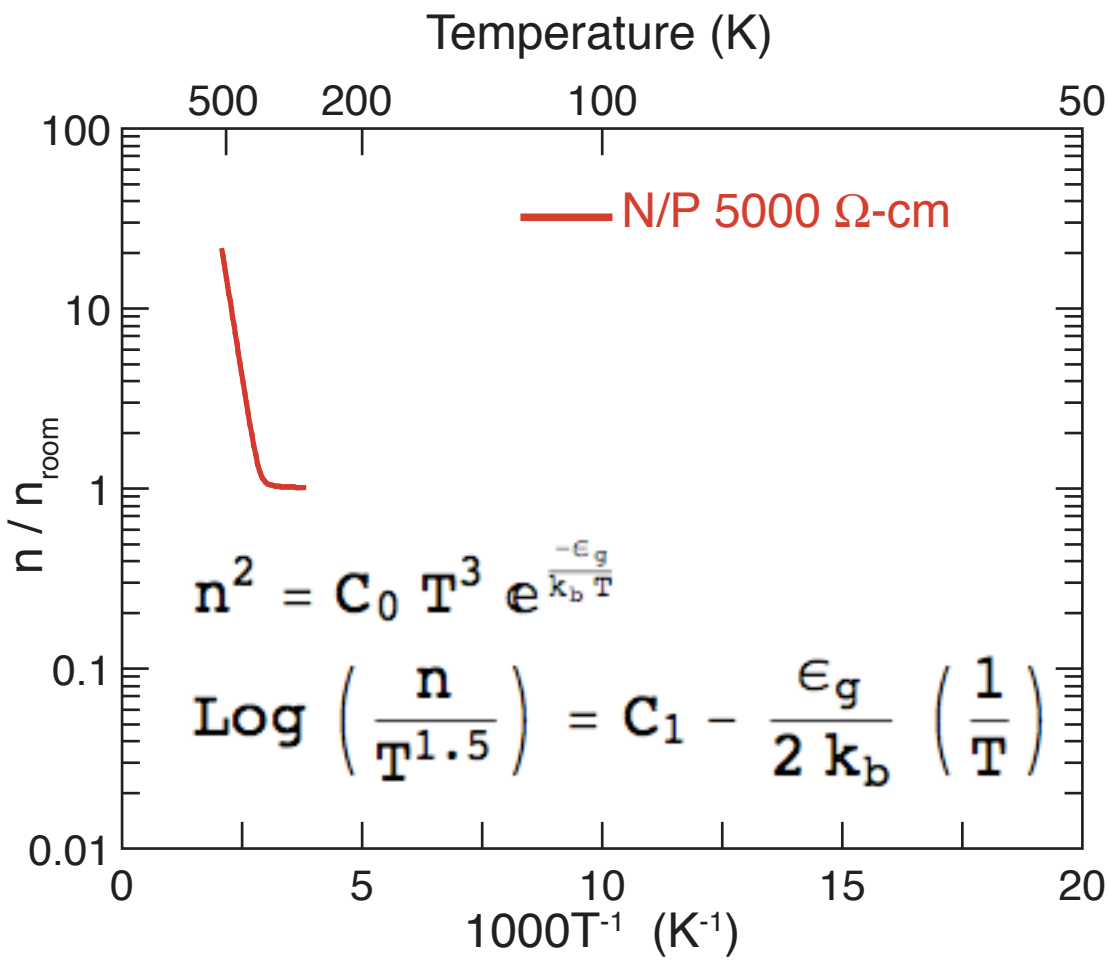


Dopant levels from Hall measurements



PRELIMINARY RESULTS

Dopant levels from Hall measurements



PRELIMINARY RESULTS

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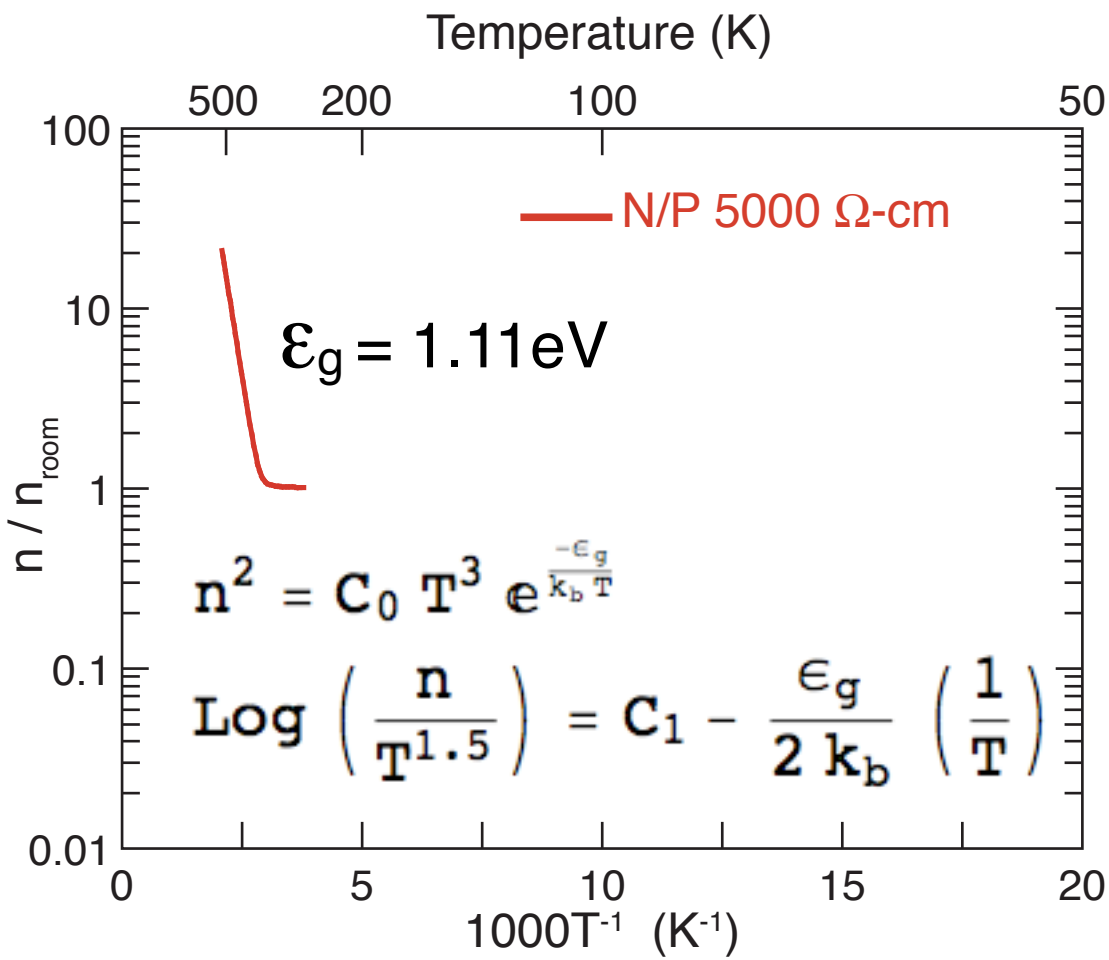

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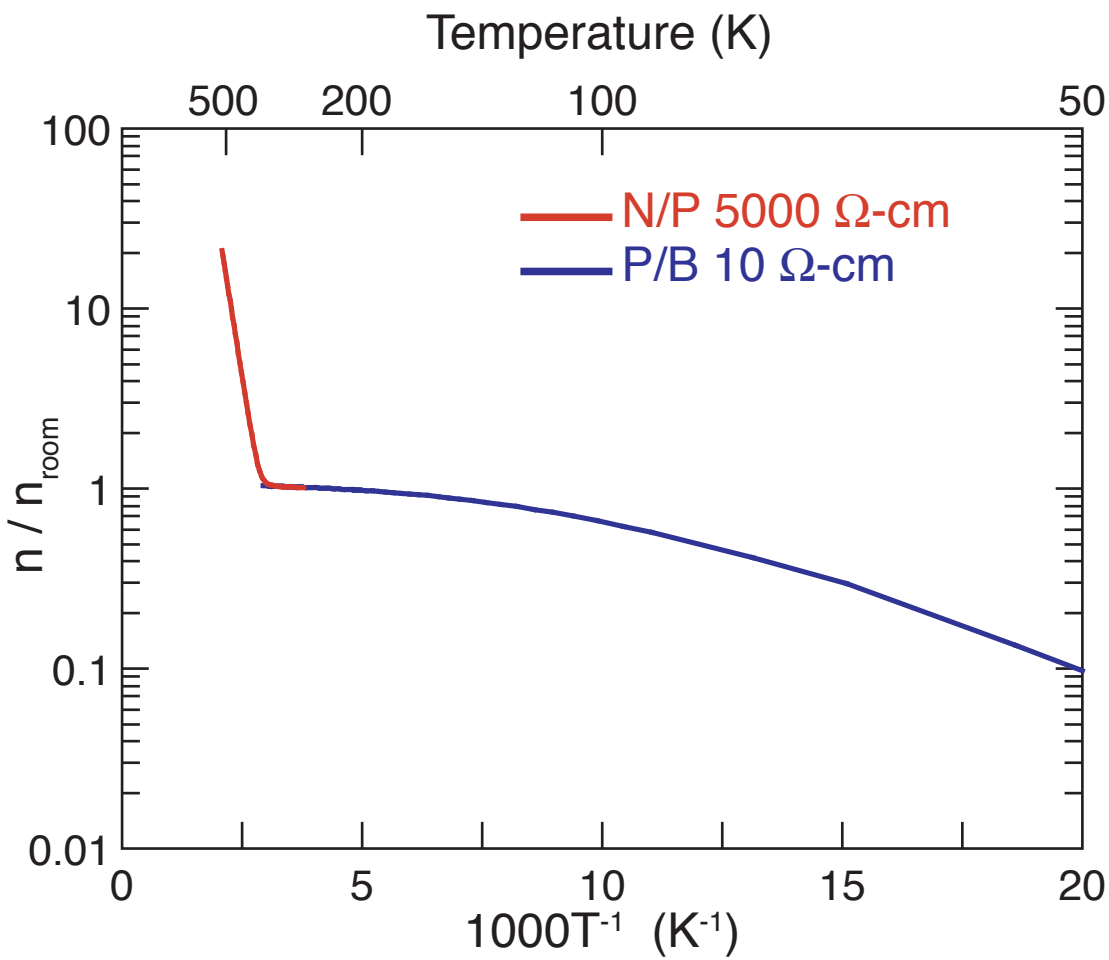

PRELIMINARY RESULTS

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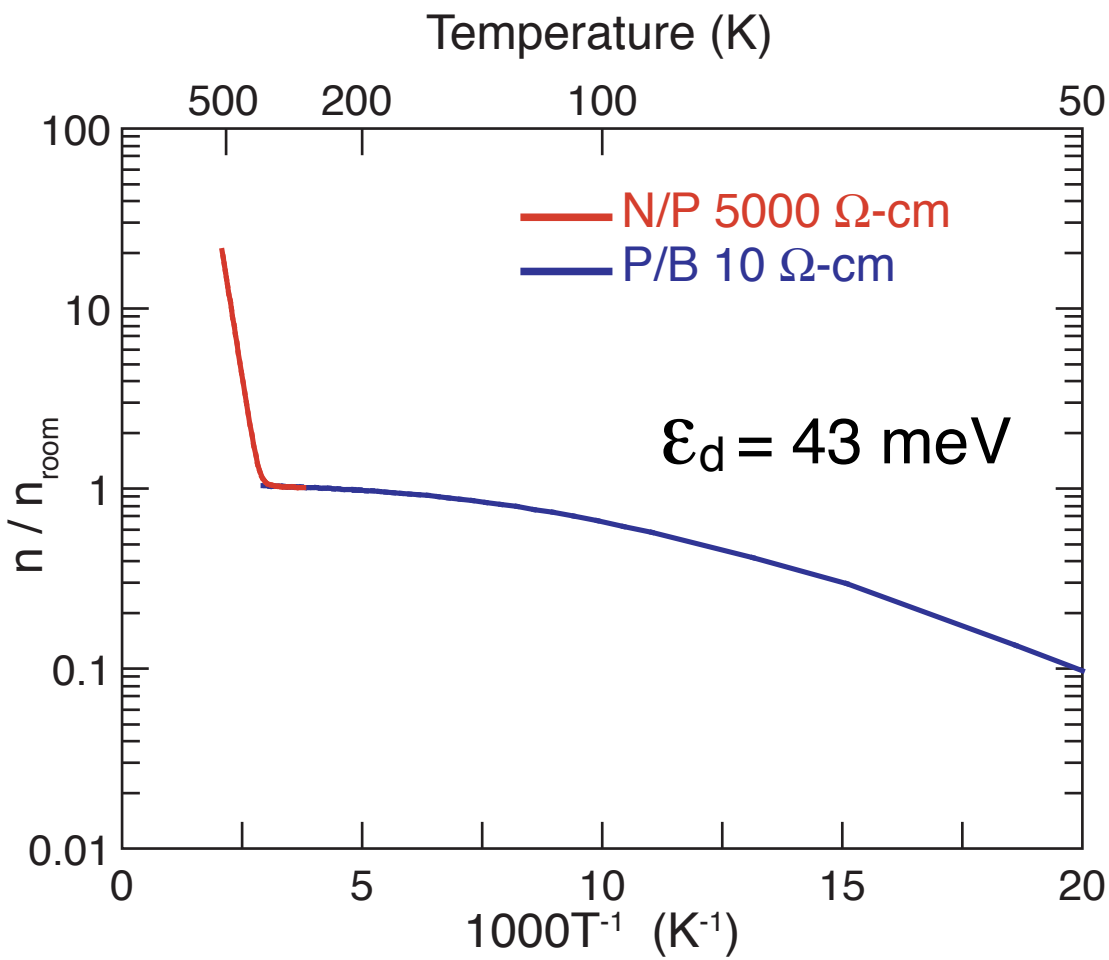

PRELIMINARY RESULTS

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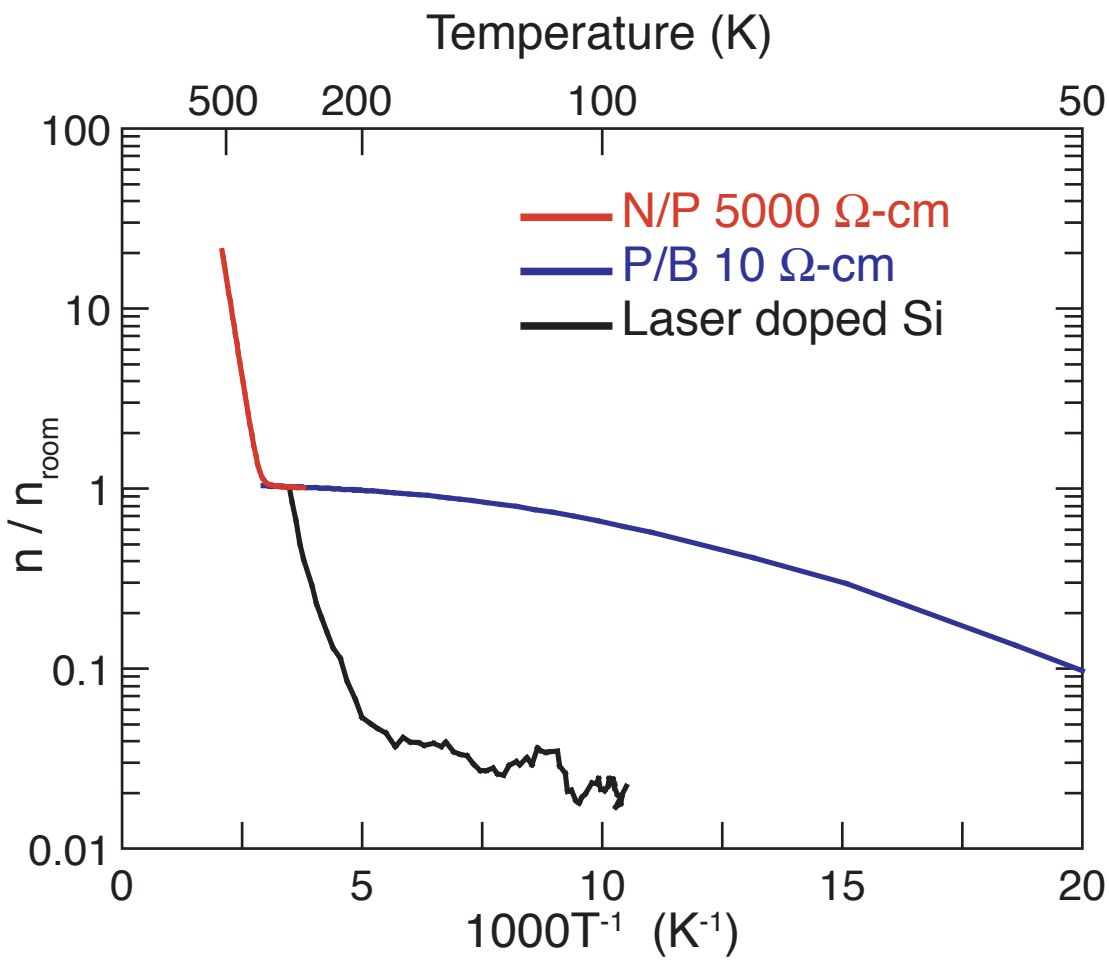

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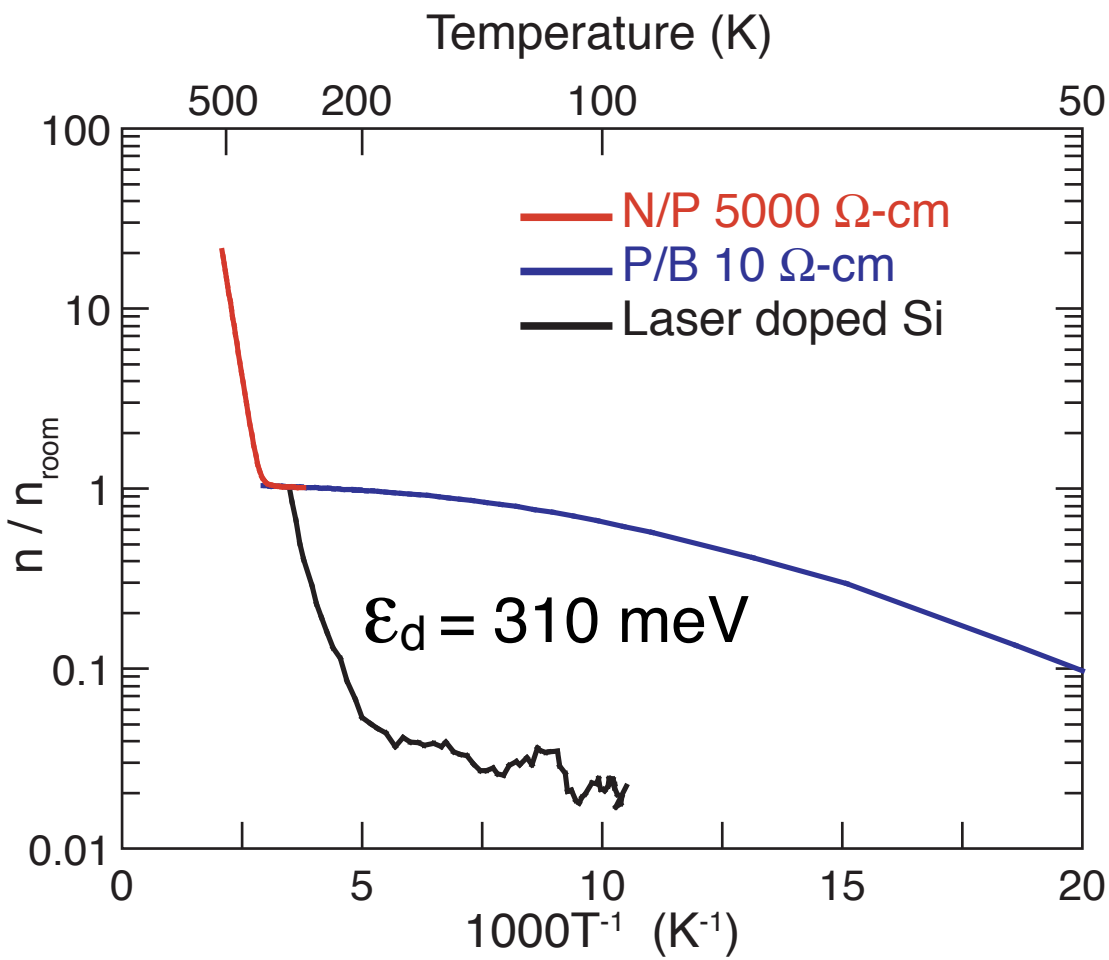
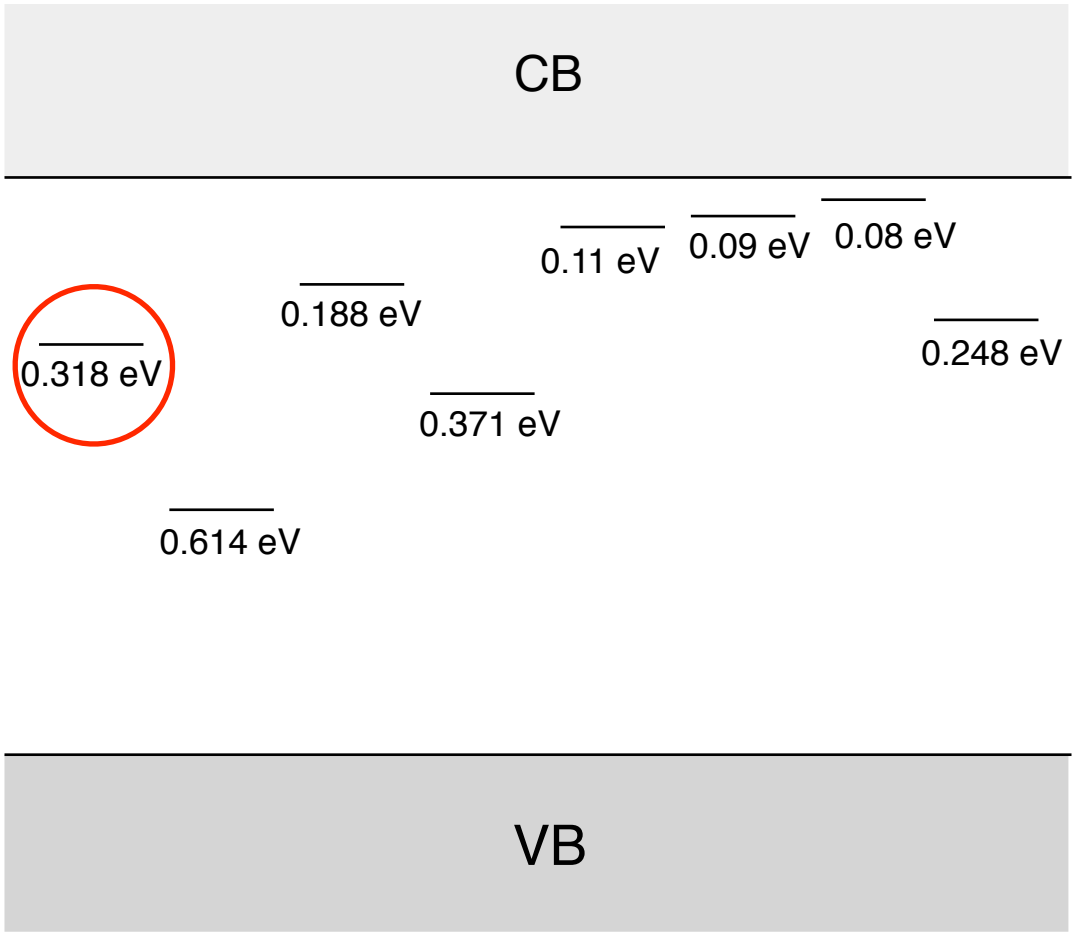
Dopant levels from Hall measurements



PRELIMINARY RESULTS

substitutional

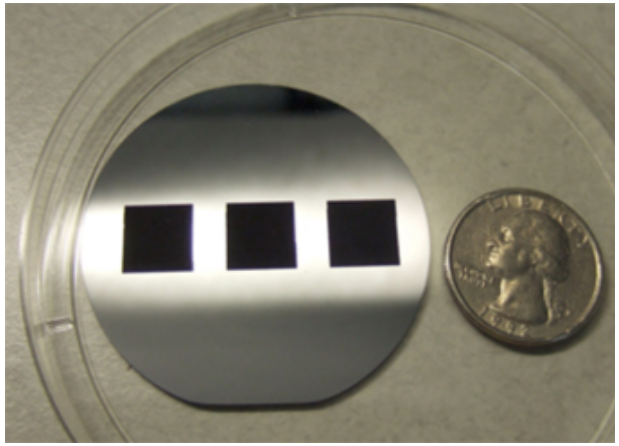


Janzén et al. , Phys. Rev. B 29, 1907 (1984)

Preliminary conclusion: S takes **substitutional** site

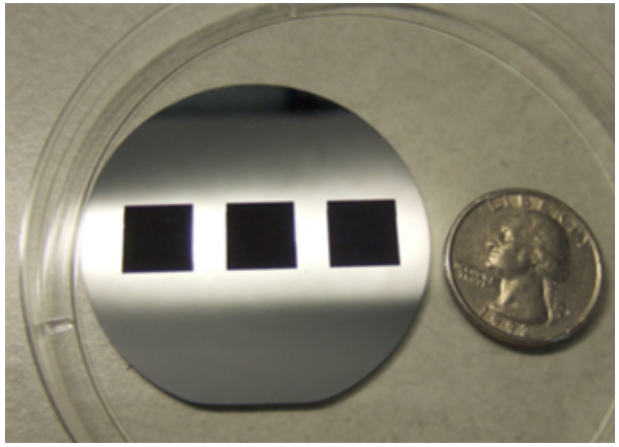
Conclusions

Conclusions



Laser doping dramatically alters optical properties

Conclusions



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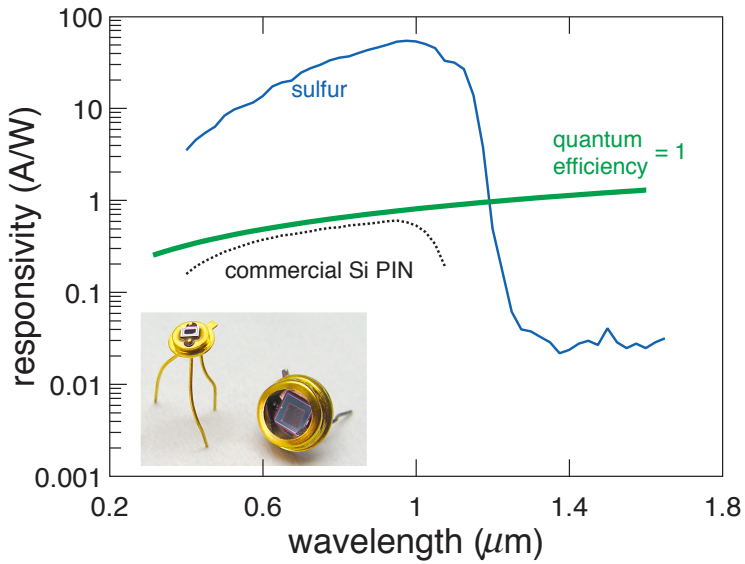
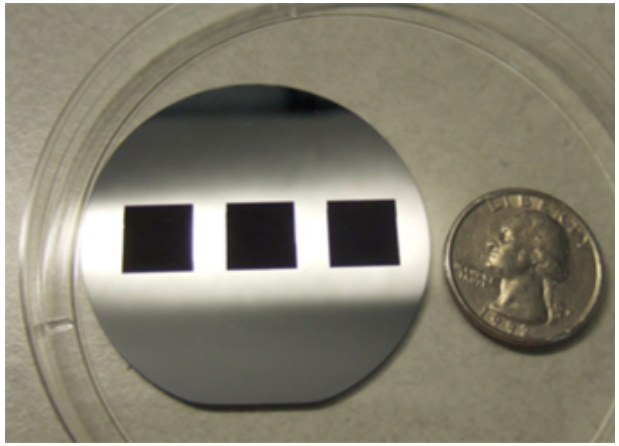


We can extend spectral range of silicon

Conclusions



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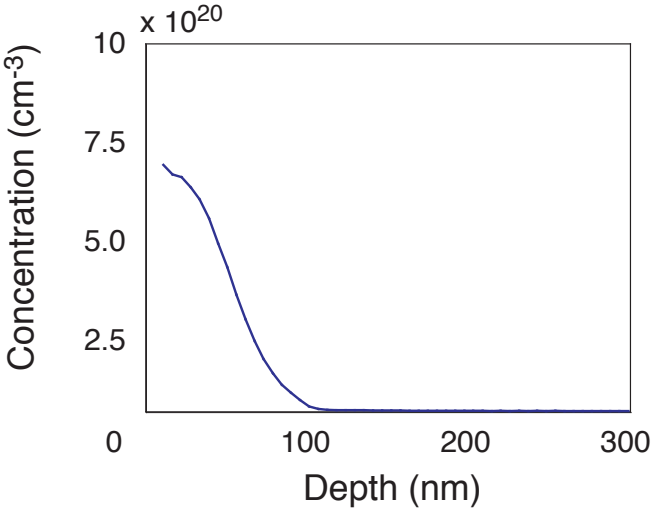
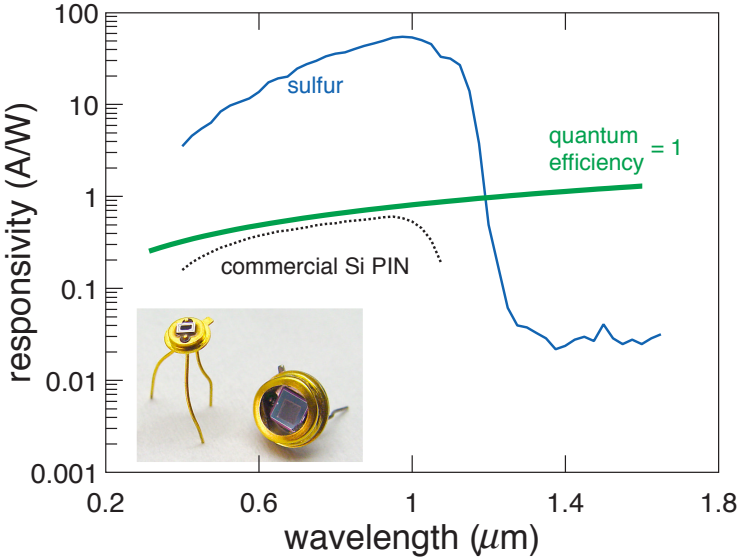


Dopants exceed equilibrium concentrations



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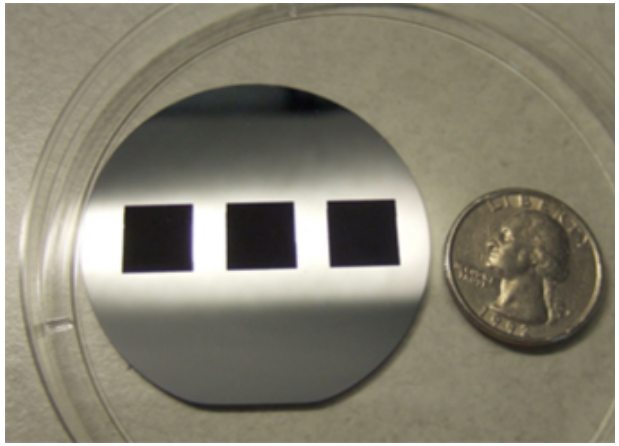

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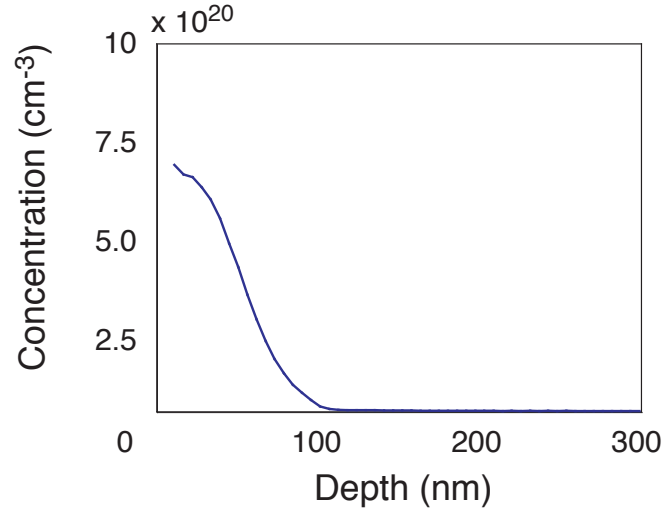

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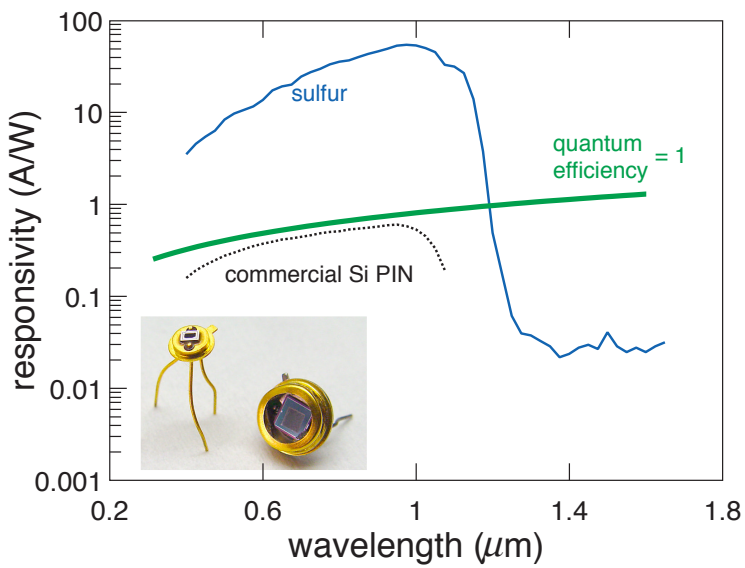

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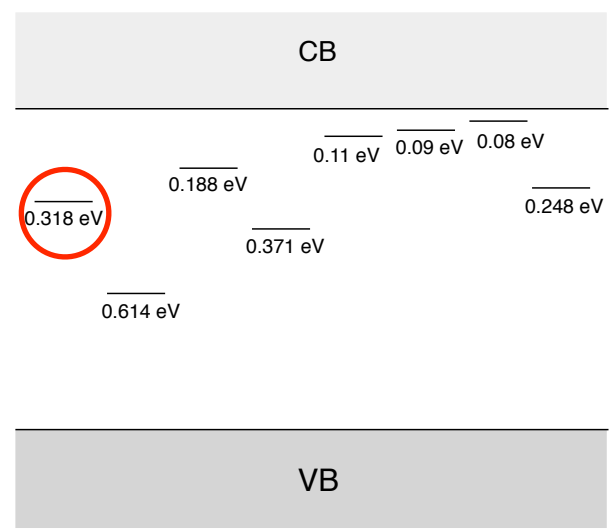


Janzén et al. , Phys. Rev. B 29, 1907 (1984)

Better knowledge of electronic structure will enable incorporation into devices

Acknowledgements

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

the Mazur Group

Funding: NSF, ARO

Thanks! Questions?

winkler@physics.harvard.edu

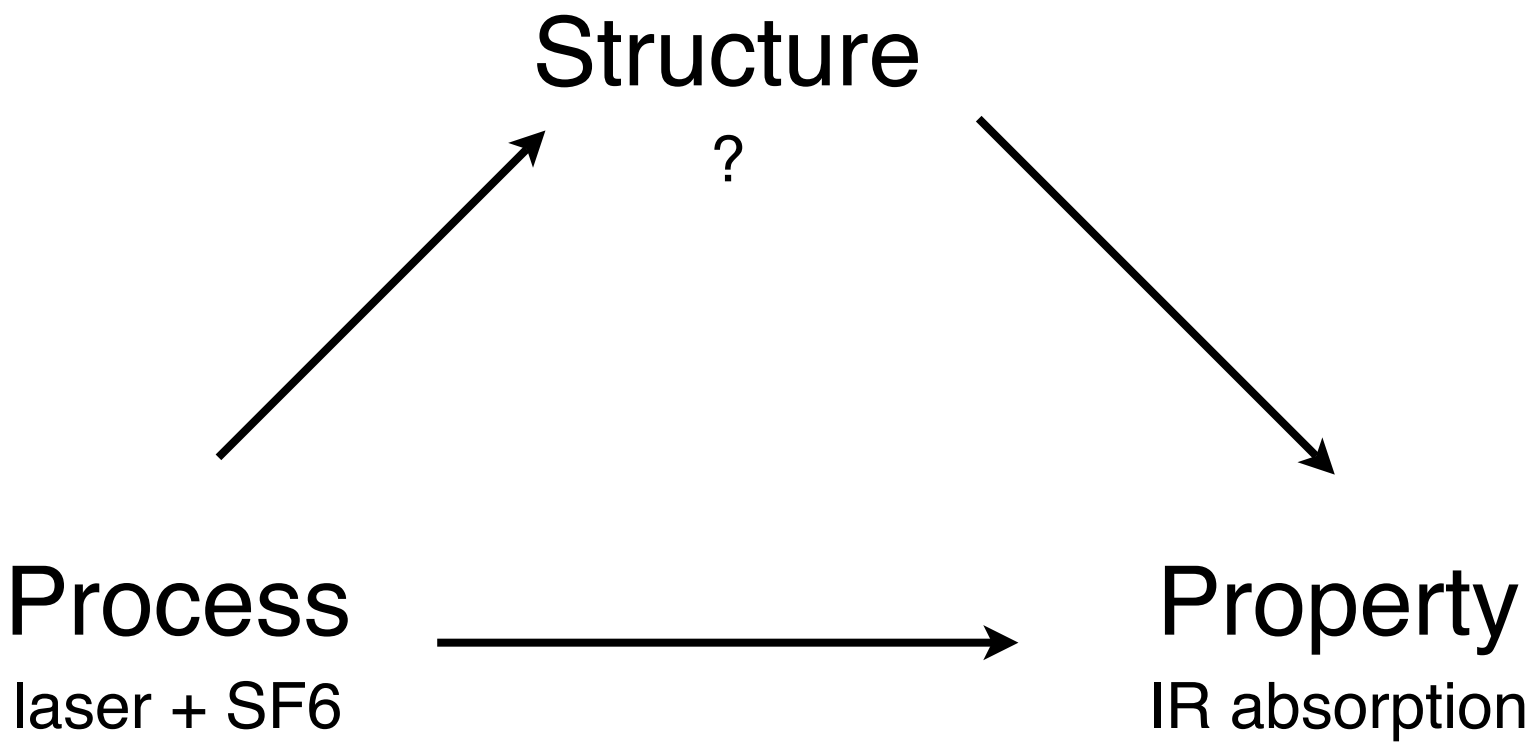
http://mazur-www.harvard.edu

END OF TALK

Process → Property

laser + SF6

IR absorption


Structure
?
Process
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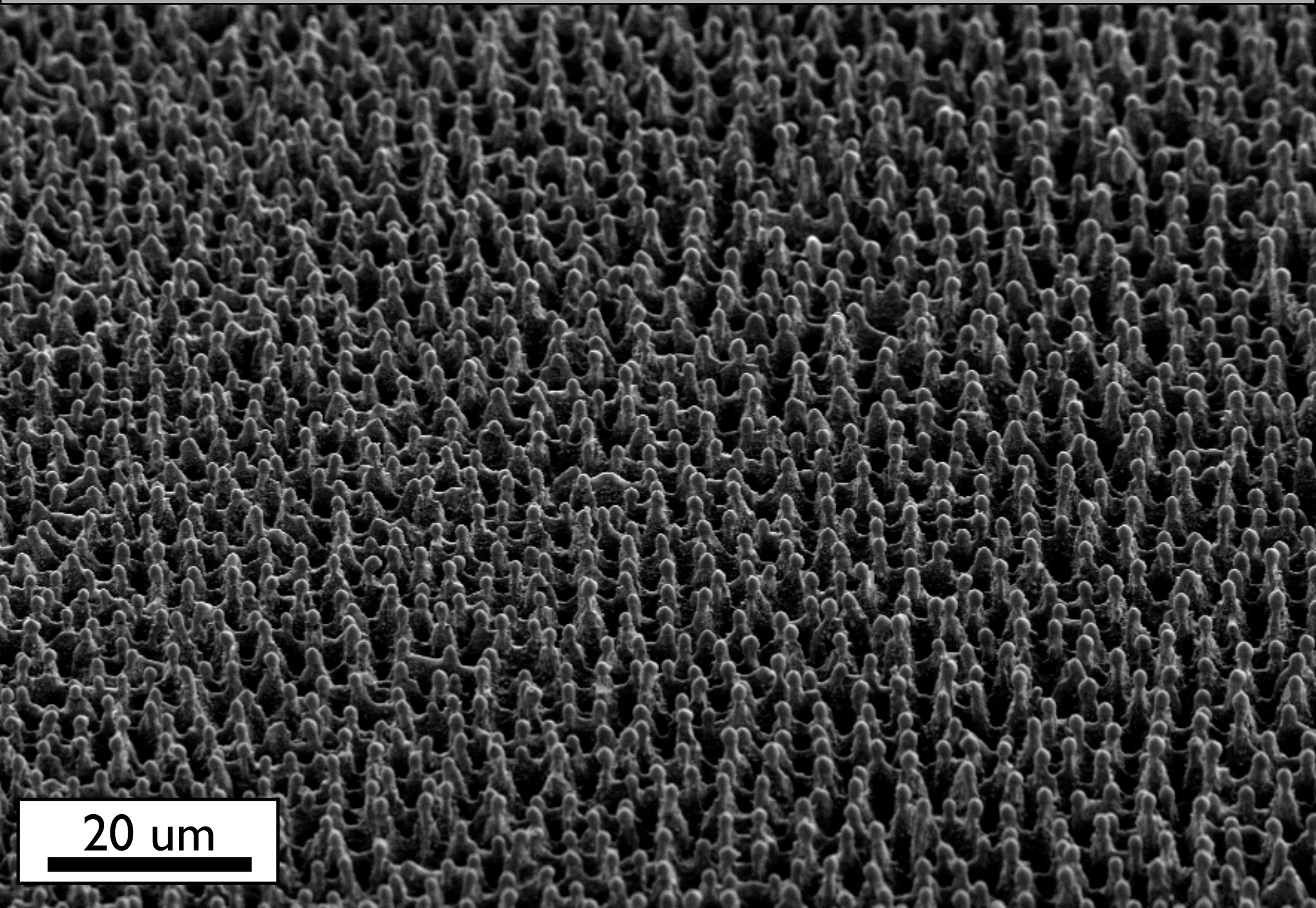
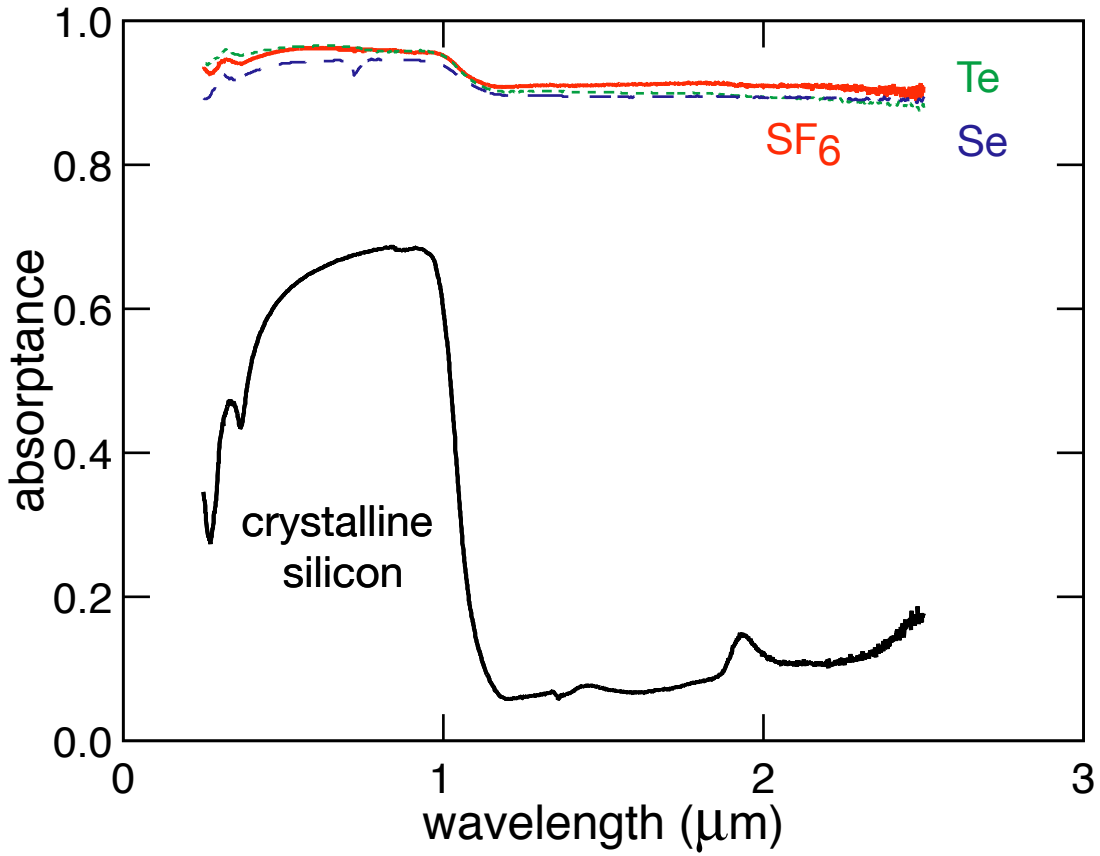
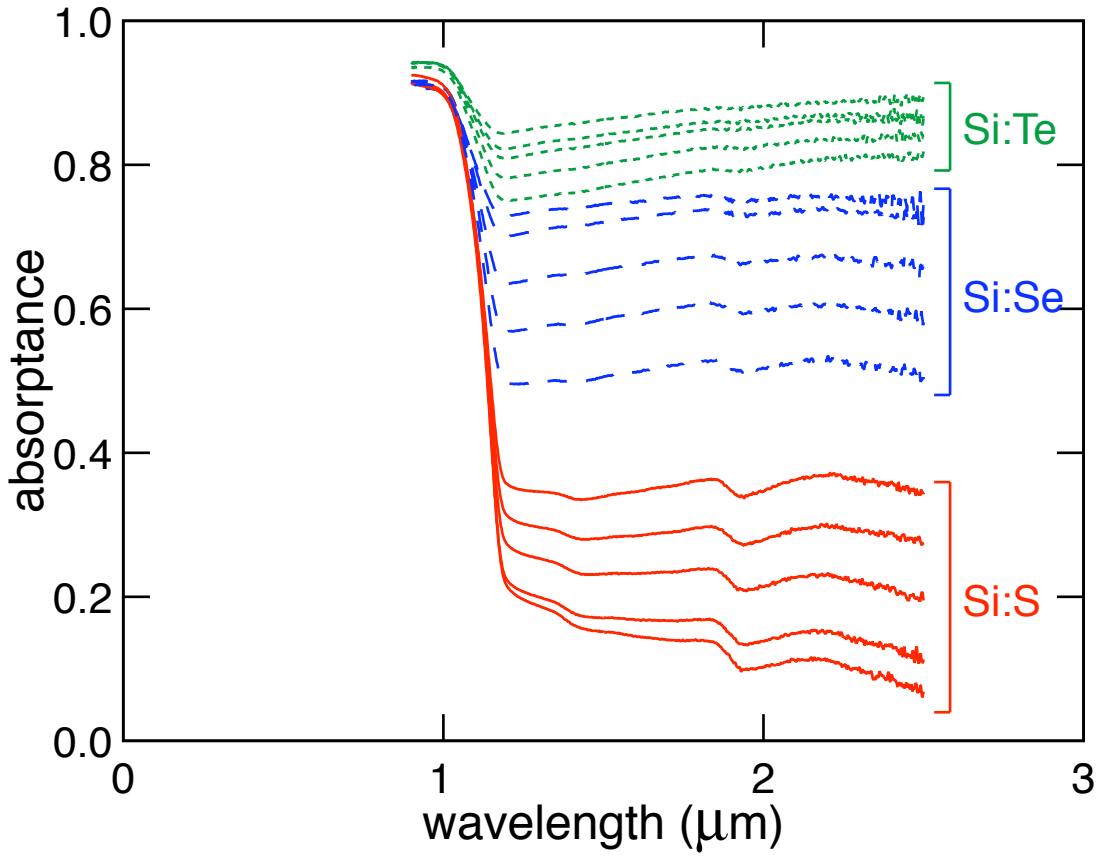
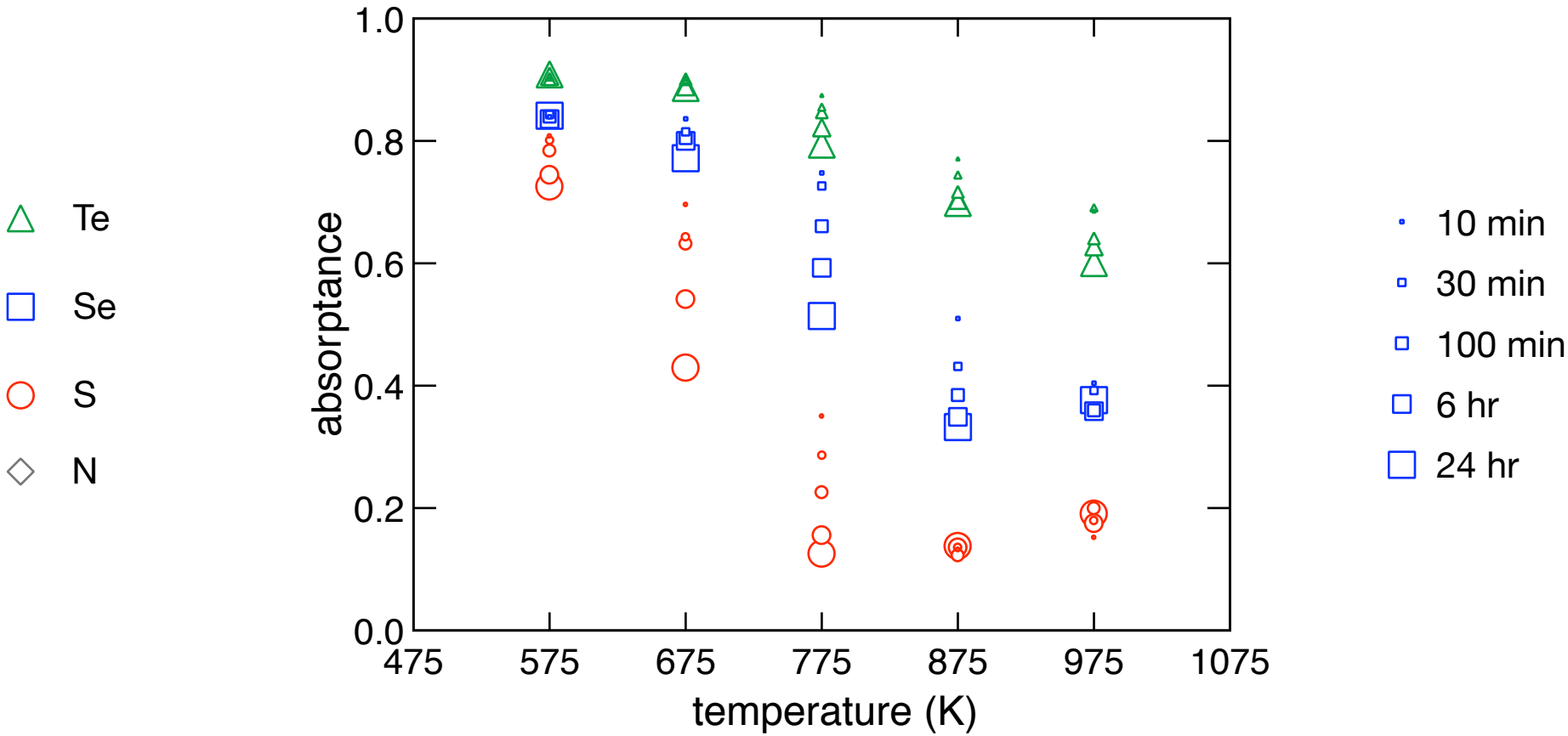
Property
IR absorption

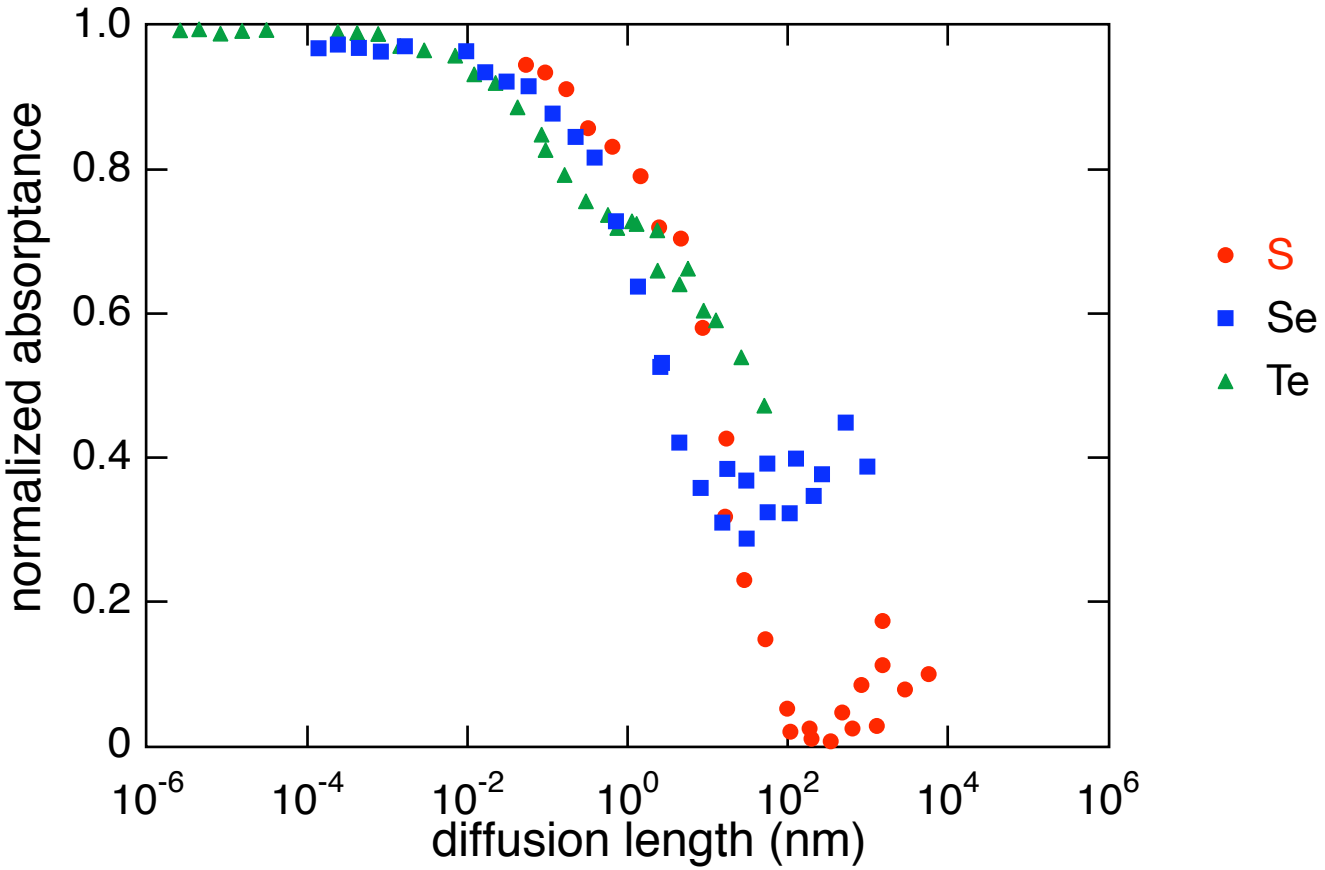

20 um


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

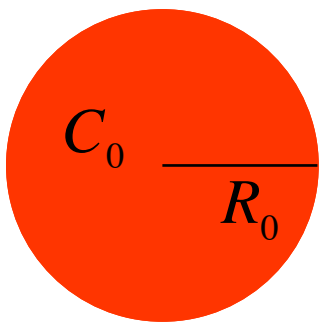

1.0
0.8
0.6
0.4
0.2
0.0
absorptance
0
1
2
3
wavelength (μm)
Si:Te
Si:Se
Si:S

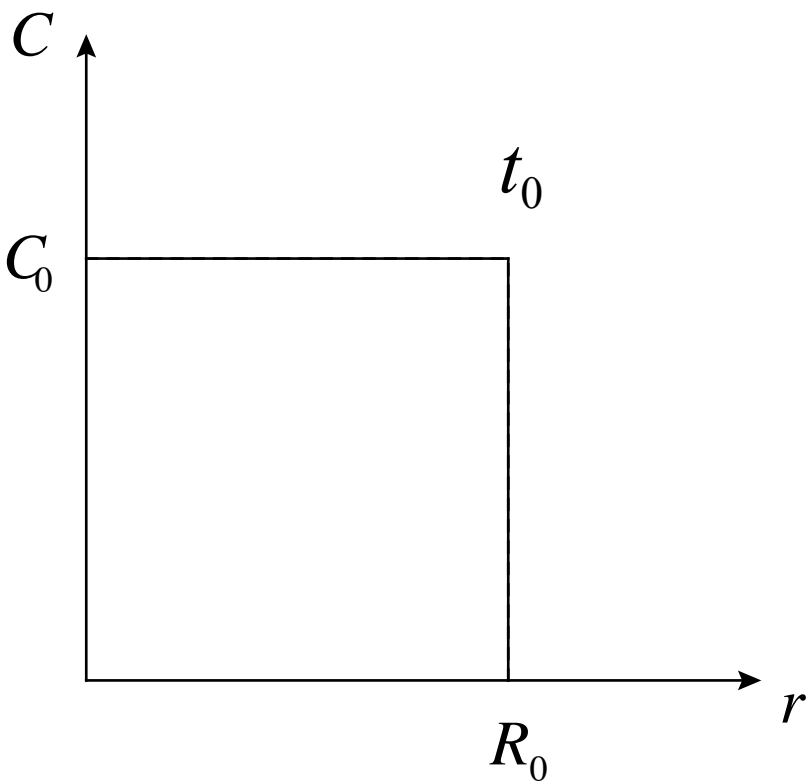


$$\text{diffusion length} = \sqrt{D_i t} = f(T,t)$$

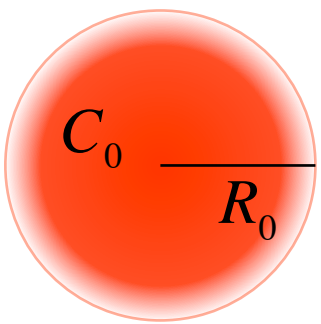

1.0
0.8
0.6
0.4
0.2
0
normalized absorptance
10^{-6}
10^{-4}
10^{-2}
10^{0}
10^{2}
10^{4}
10^{6}
diffusion length (nm)
S
Se
Te

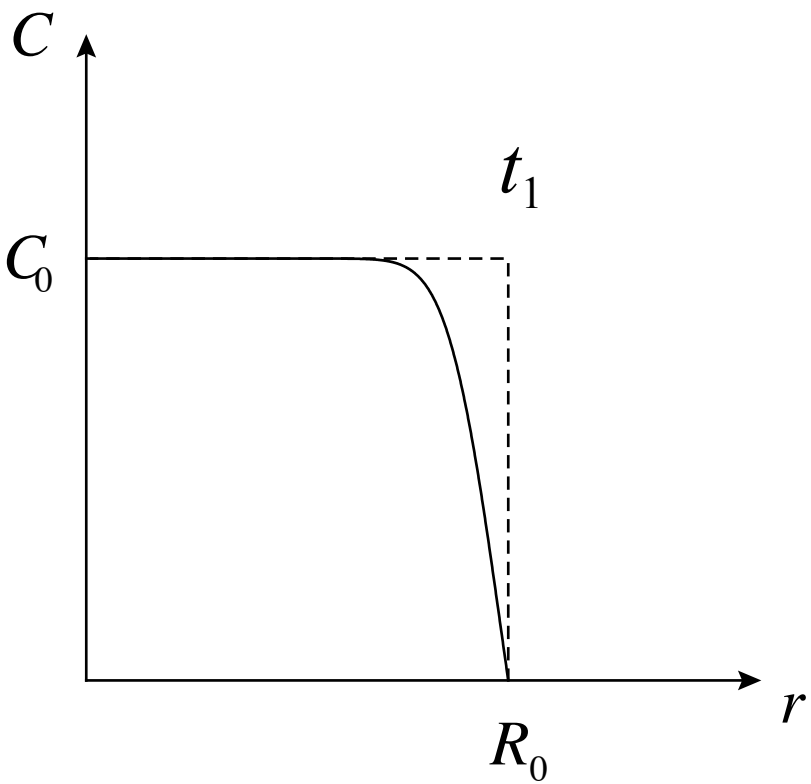
Could this diffusion-related drop in absorptance be governed by grain size?



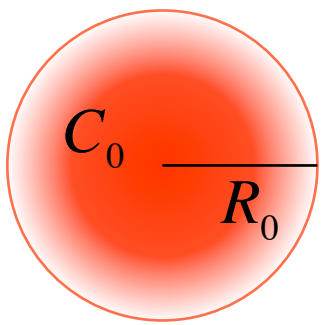


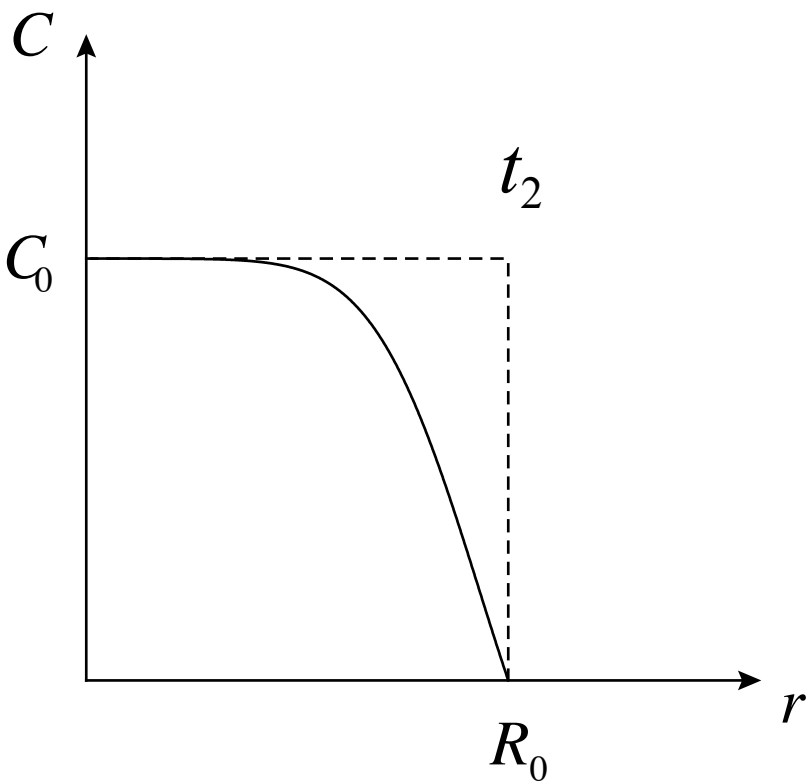
Could this diffusion-related drop in absorptance be governed by grain size?



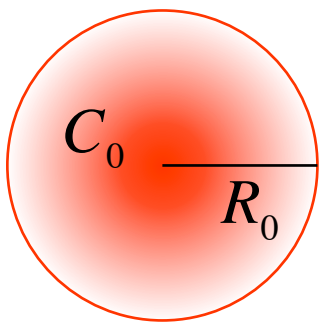


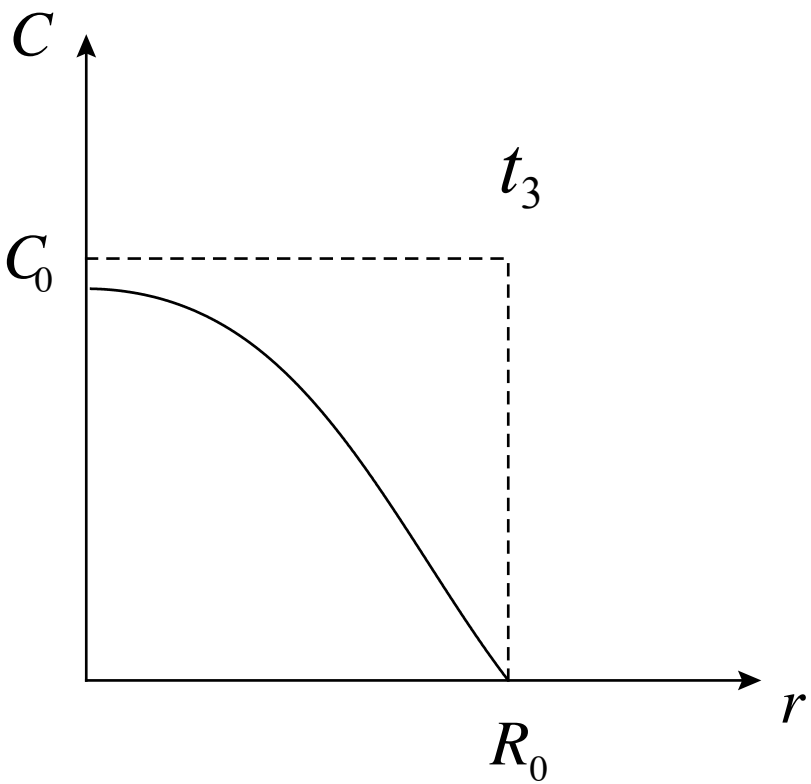
Could this diffusion-related drop in absorptance be governed by grain size?



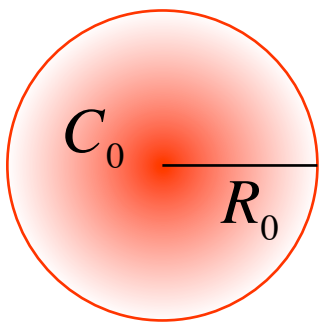


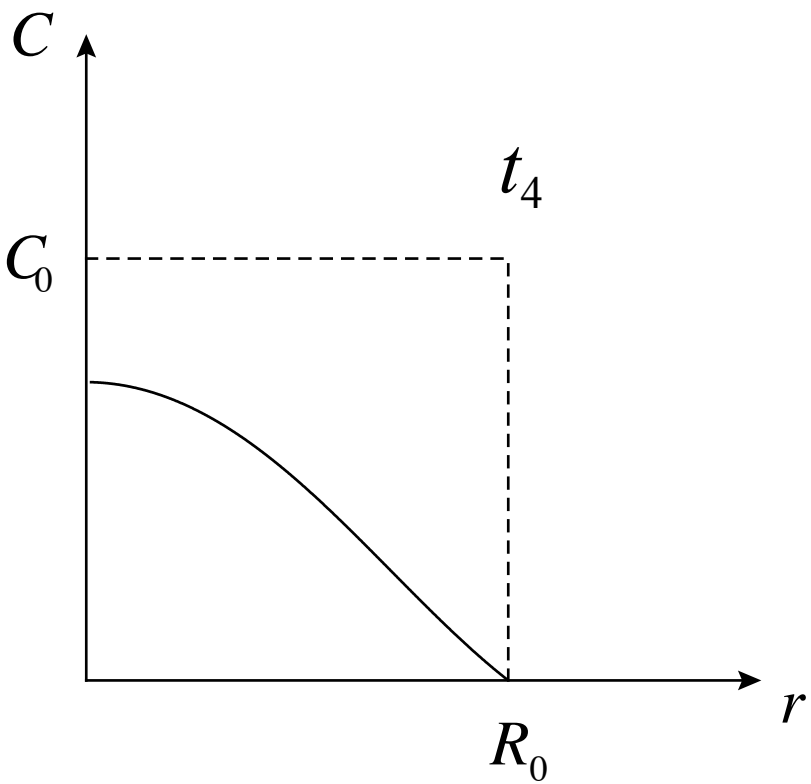
Could this diffusion-related drop in absorptance be governed by grain size?



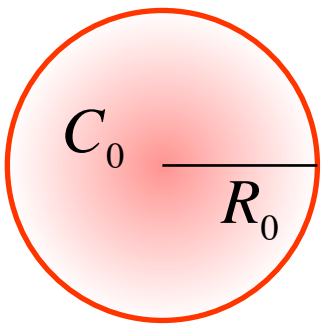


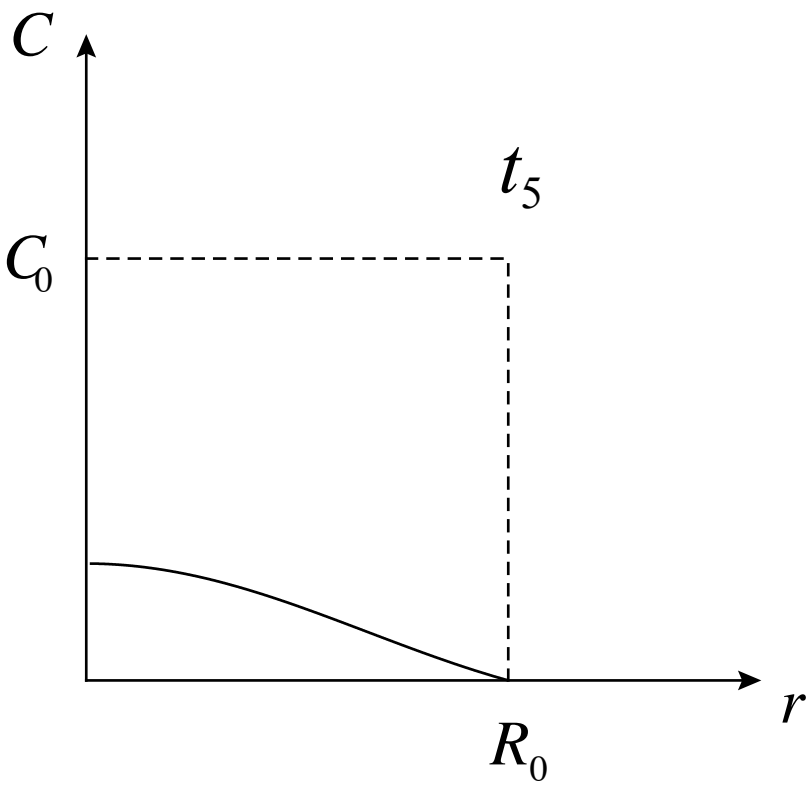
Could this diffusion-related drop in absorptance be governed by grain size?



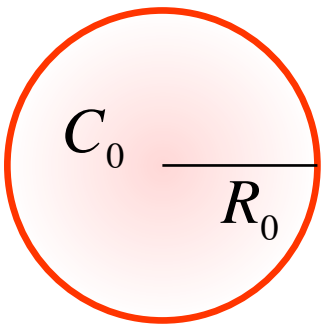


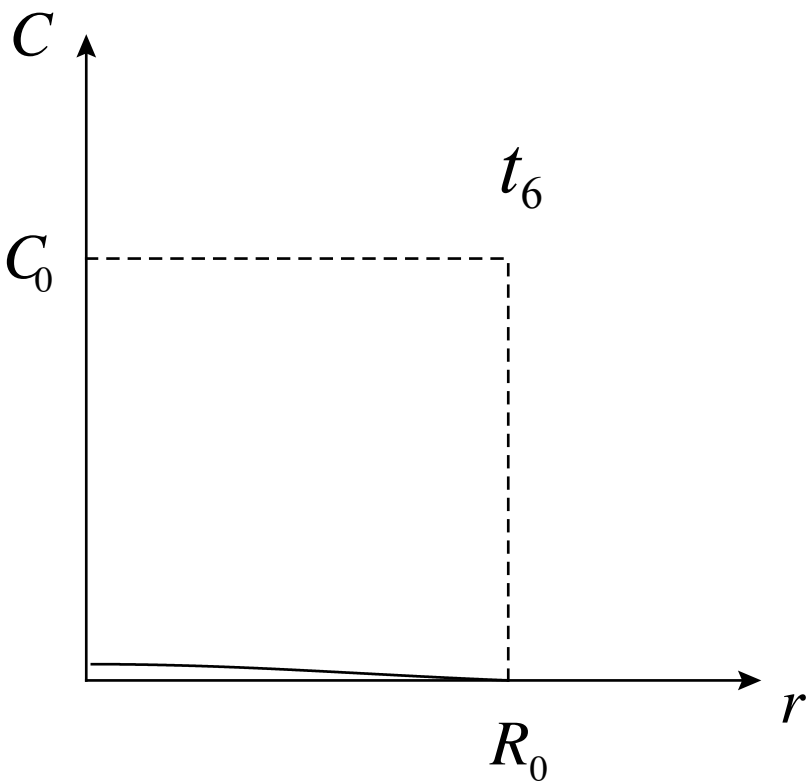
Could this diffusion-related drop in absorptance be governed by grain size?

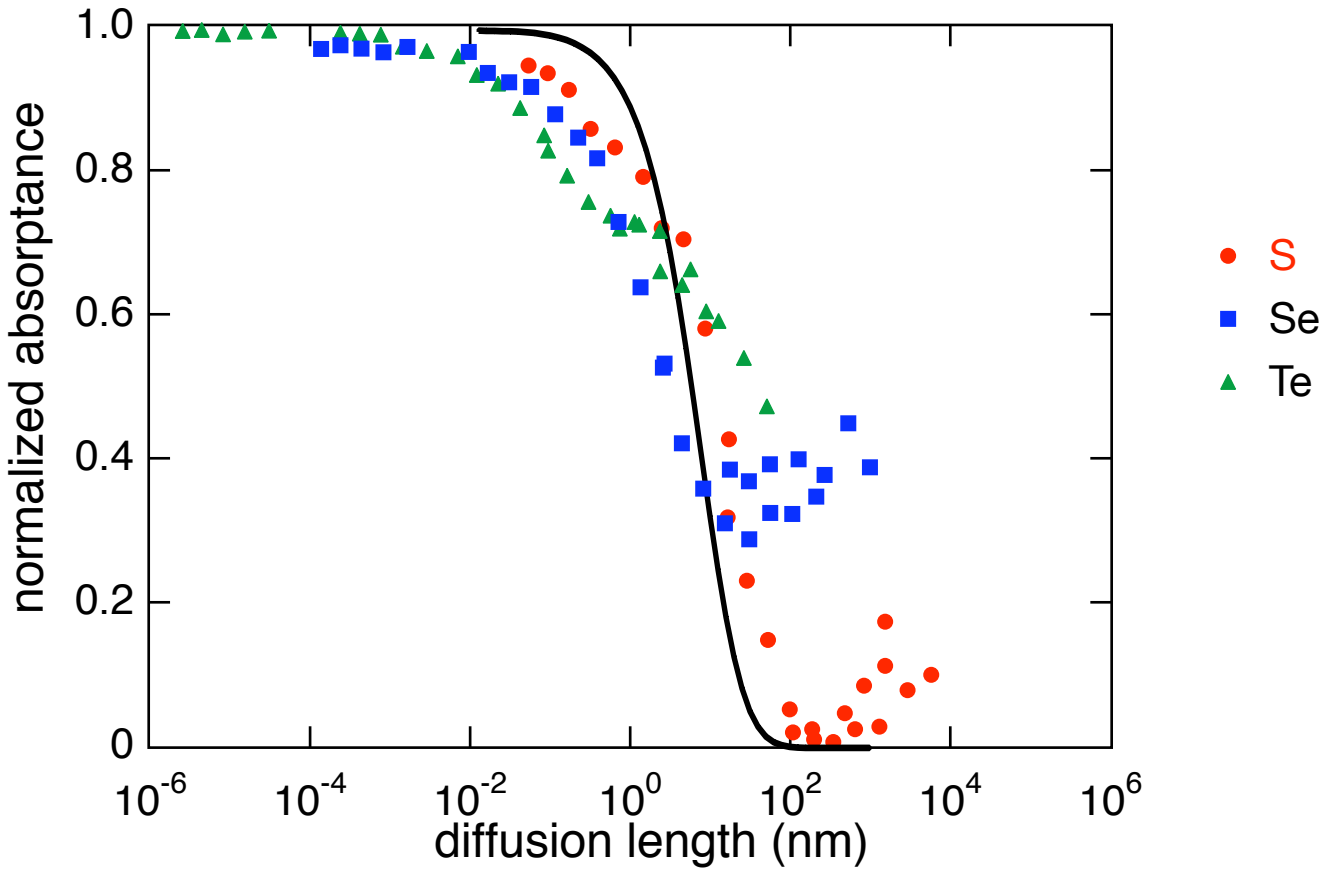




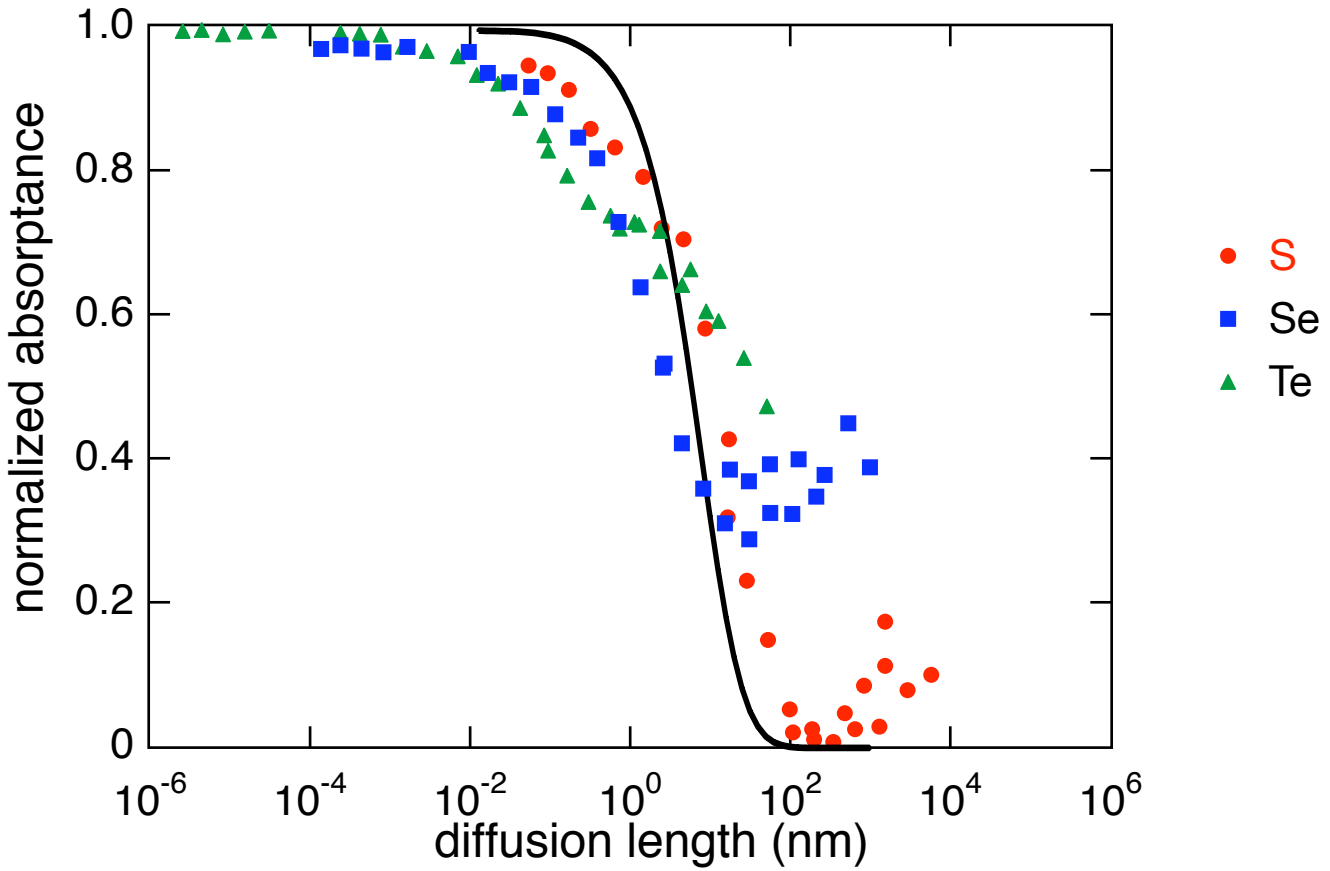
Could this diffusion-related drop in absorptance be governed by grain size?

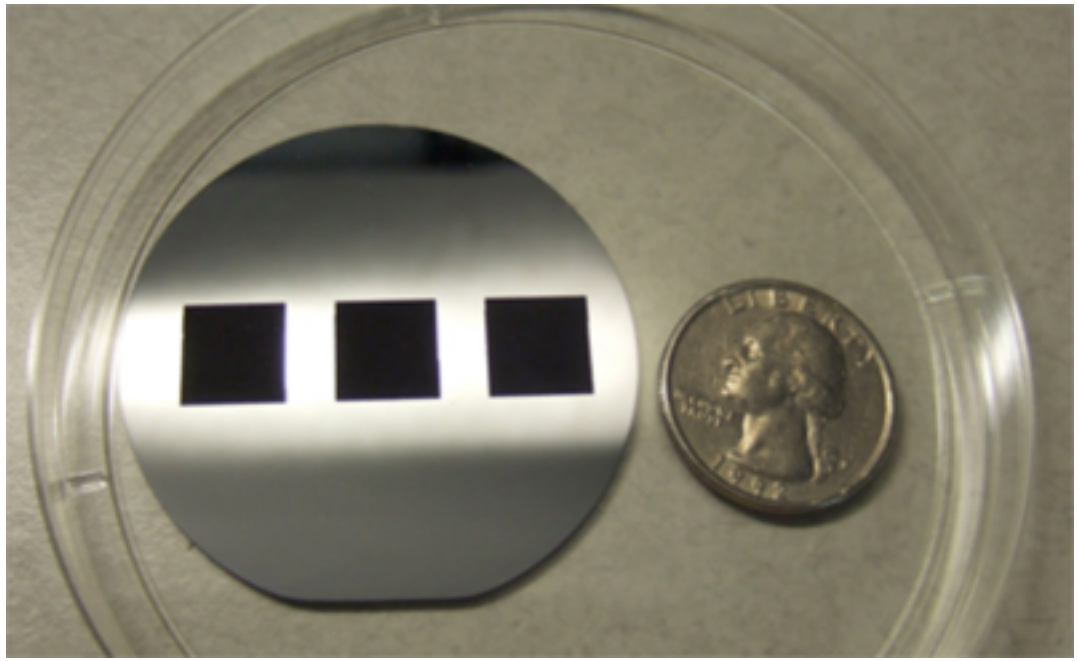




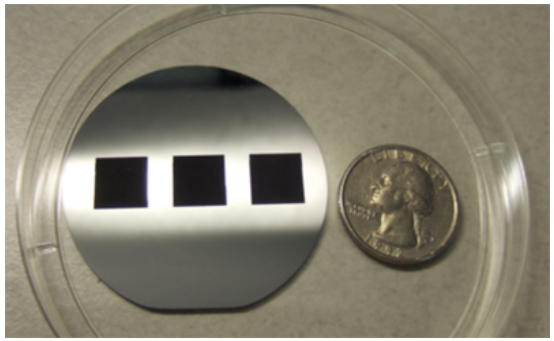

1.0
0.8
0.6
0.4
0.2
0
normalized absorptance
10^{-6}
10^{-4}
10^{-2}
10^{0}
10^{2}
10^{4}
10^{6}
diffusion length (nm)
S
Se
Te

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

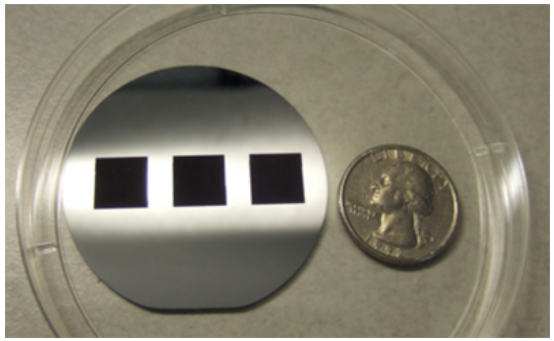


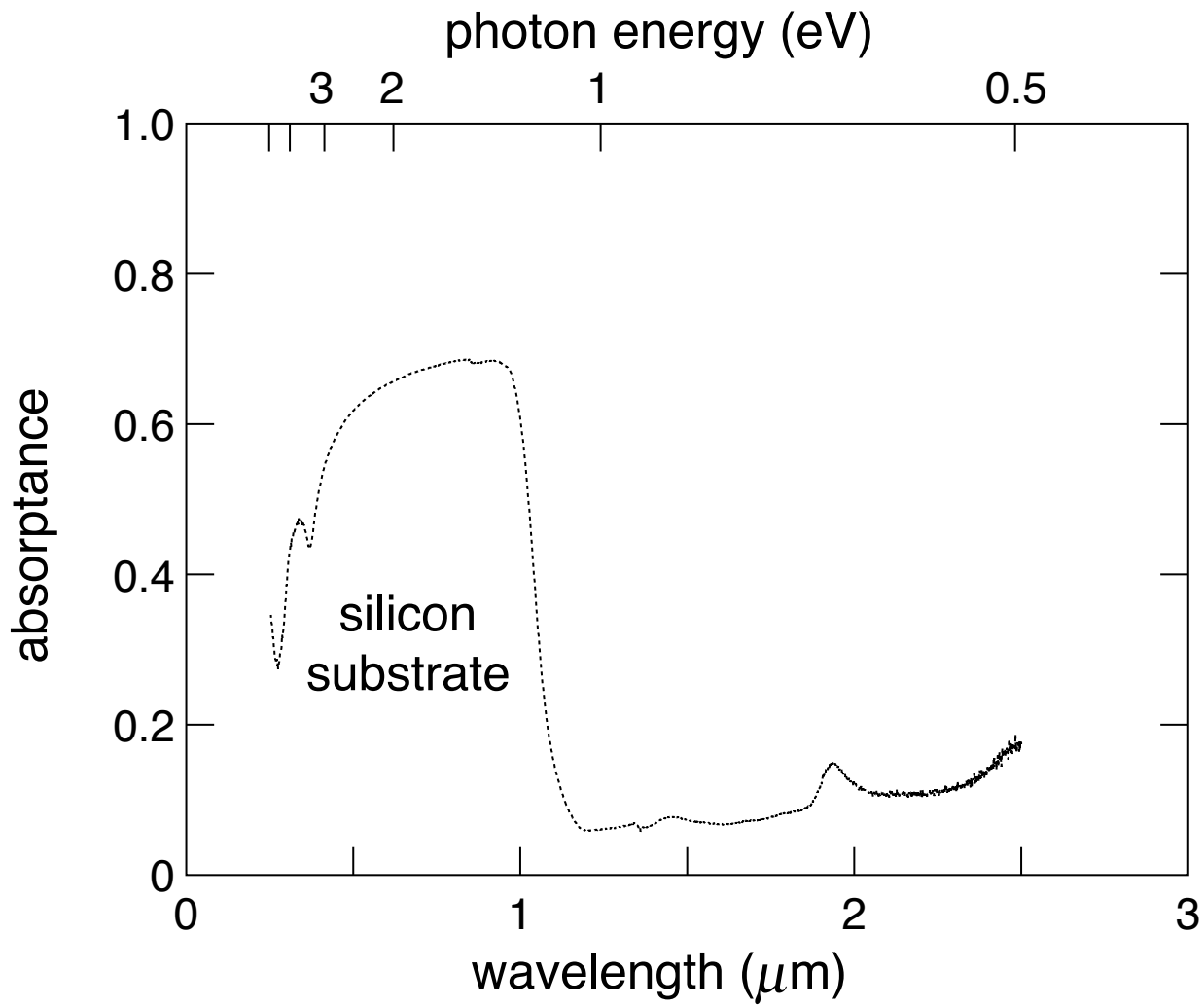


fs laser
Sulfur
compound

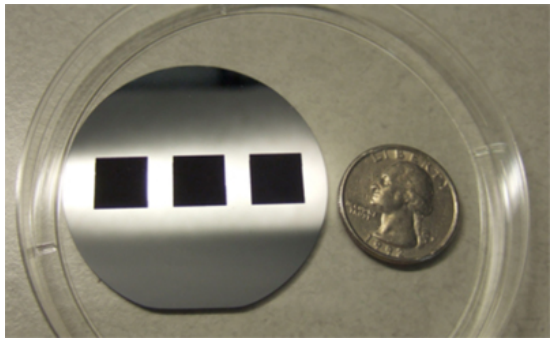


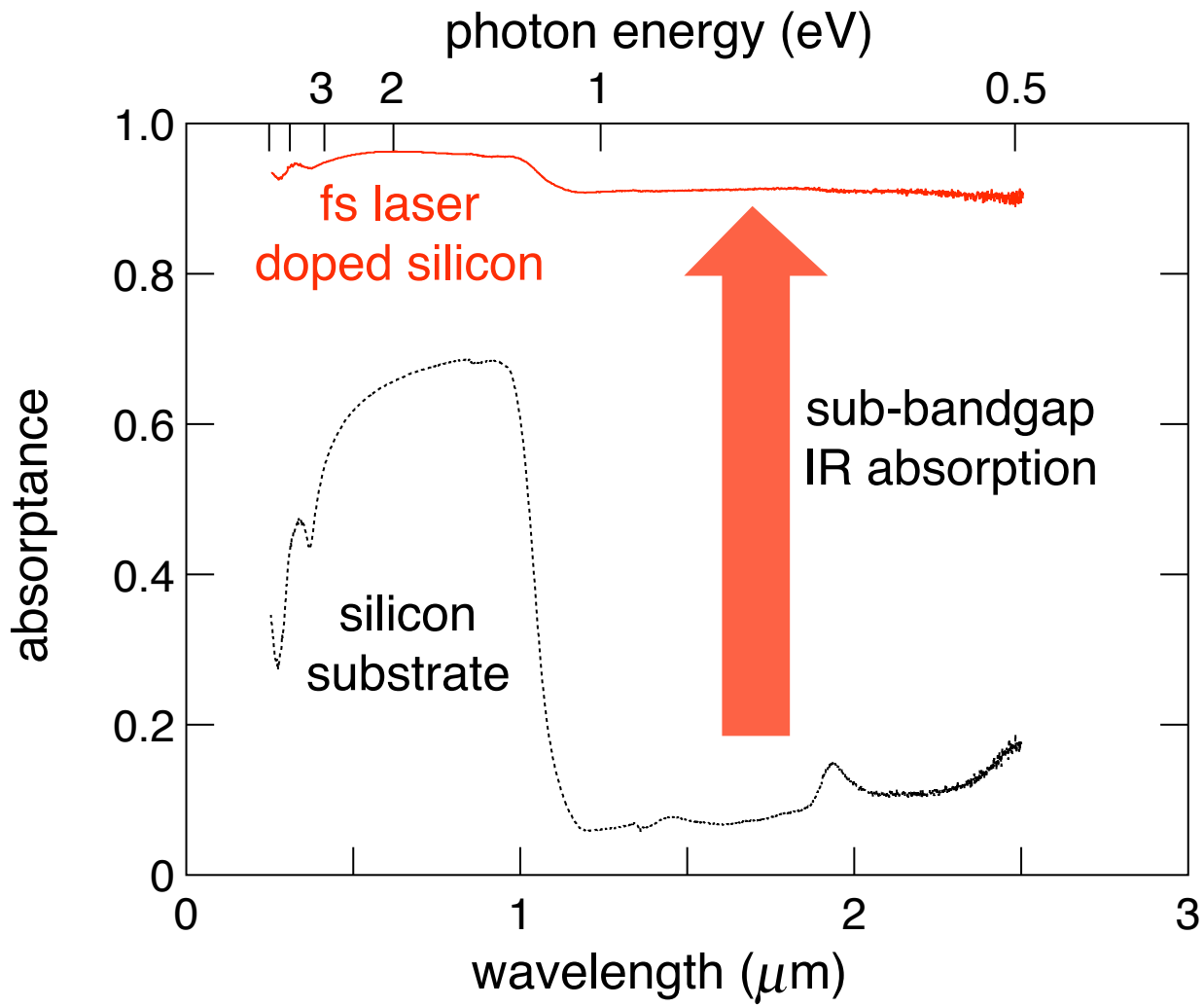
fs laser
Sulfur
compound



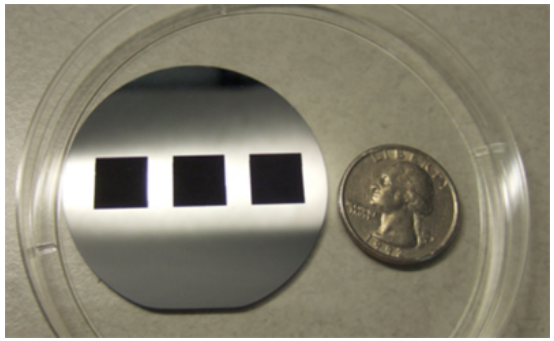

photon energy (eV)
3
2
1
0.5
1.0
0.8
0.6
0.4
0.2
0
absorptance
silicon
substrate
0
1
2
3
wavelength (μm)

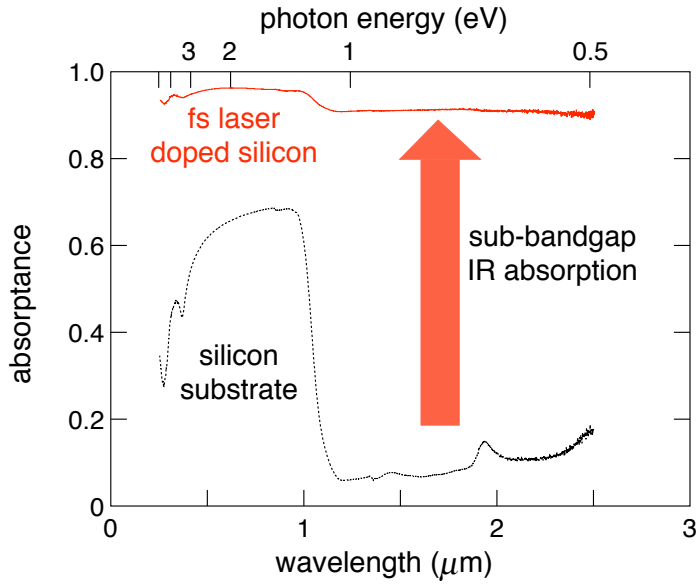
fs laser
Sulfur
compound



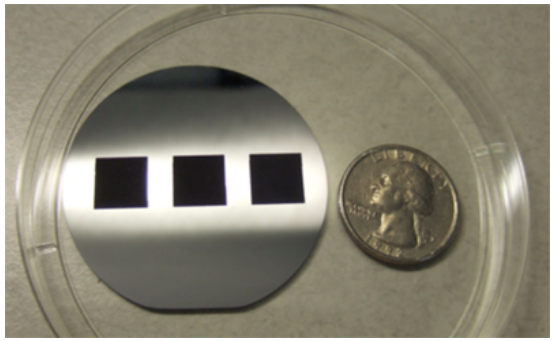

photon energy (eV)
3
2
1
0.5
1.0
0.8
0.6
0.4
0.2
0
absorptance
fs laser
doped silicon
sub-bandgap
IR absorption
silicon
substrate
0
1
2
3
wavelength (μm)

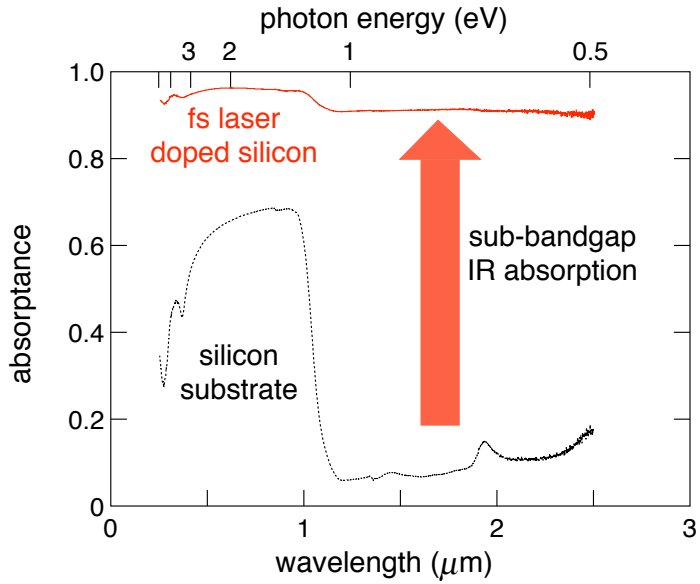
fs laser
Sulfur
compound

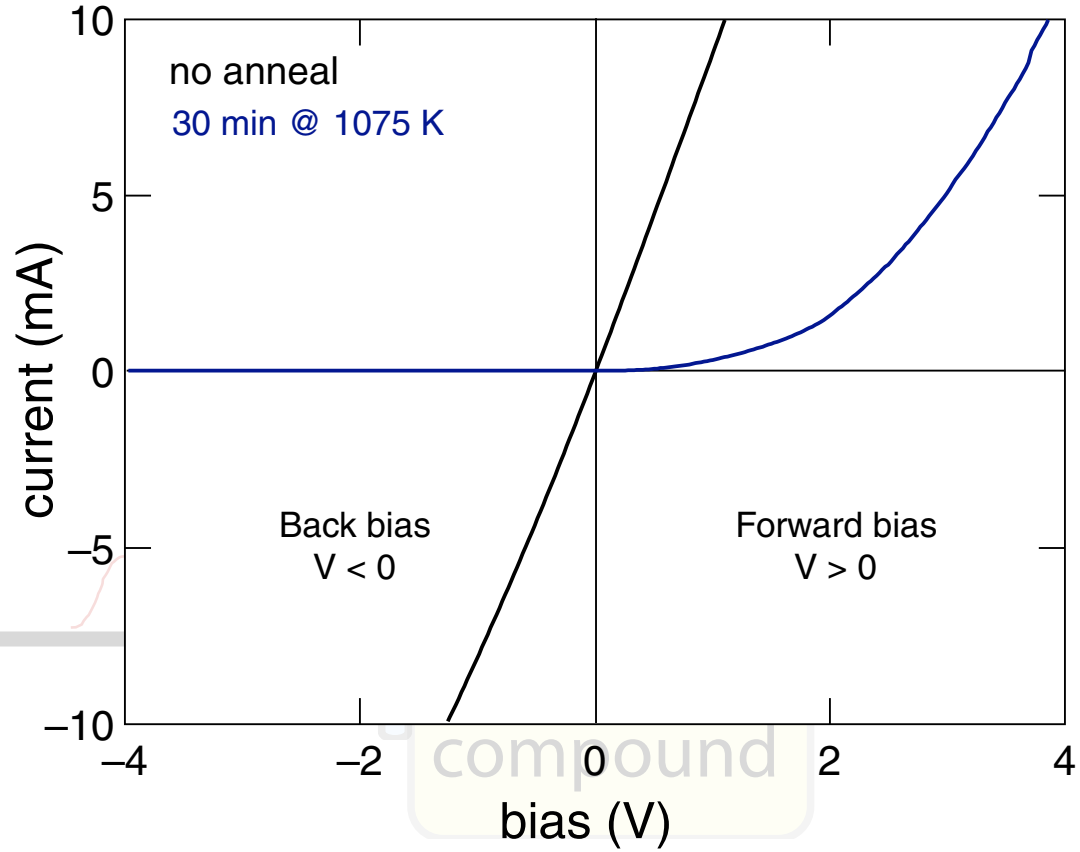



photon energy (eV)
3
2
1
0.5
1.0
0.8
0.6
0.4
0.2
0
absorptance
fs laser
doped silicon
sub-bandgap
IR absorption
silicon
substrate
0
1
2
3
wavelength (μm)

fs laser
Sulfur
compound

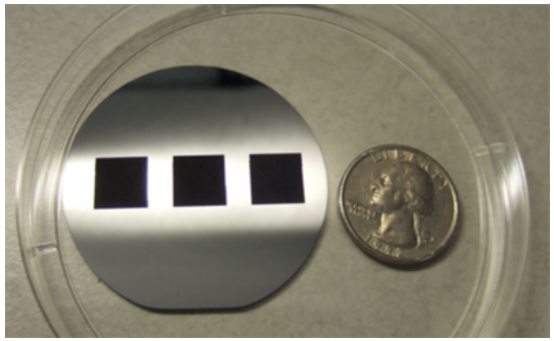


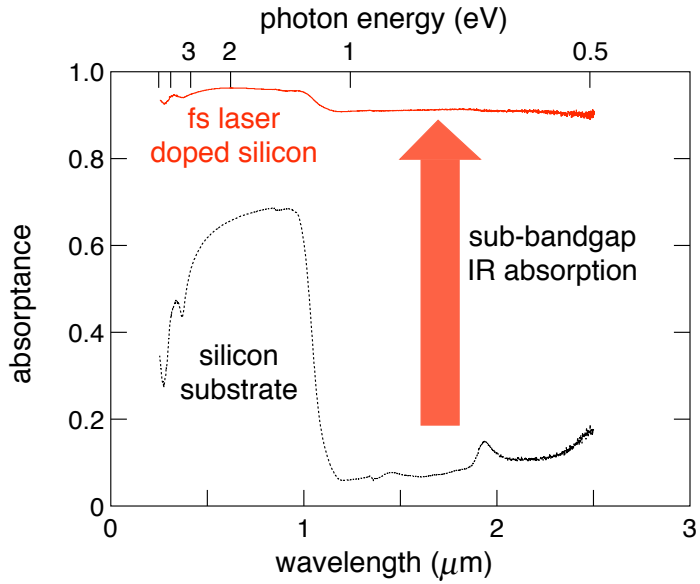


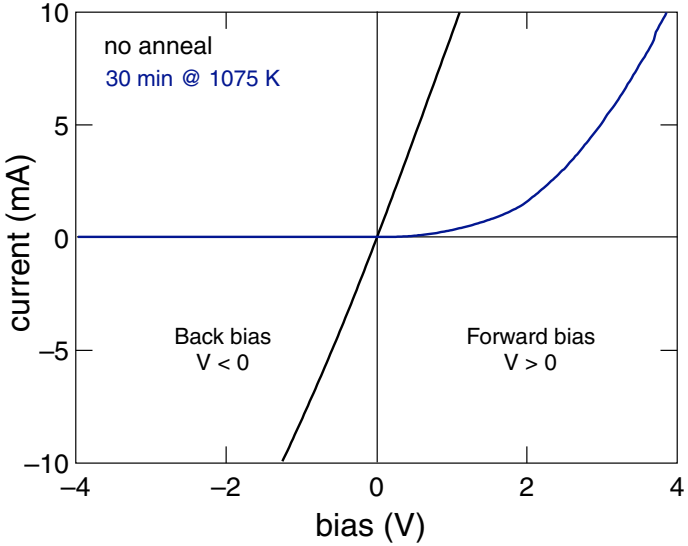


fs laser

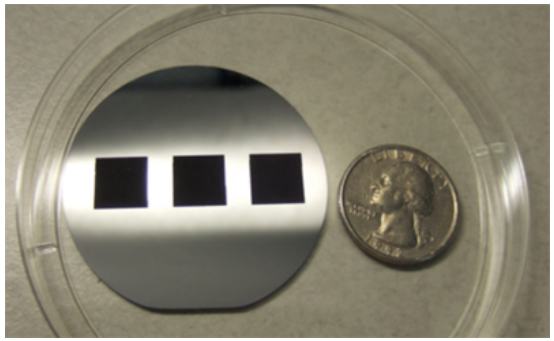
compound

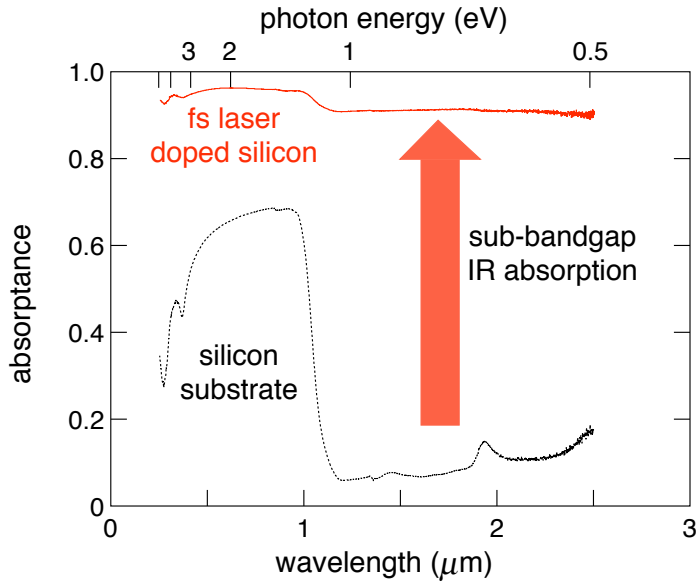


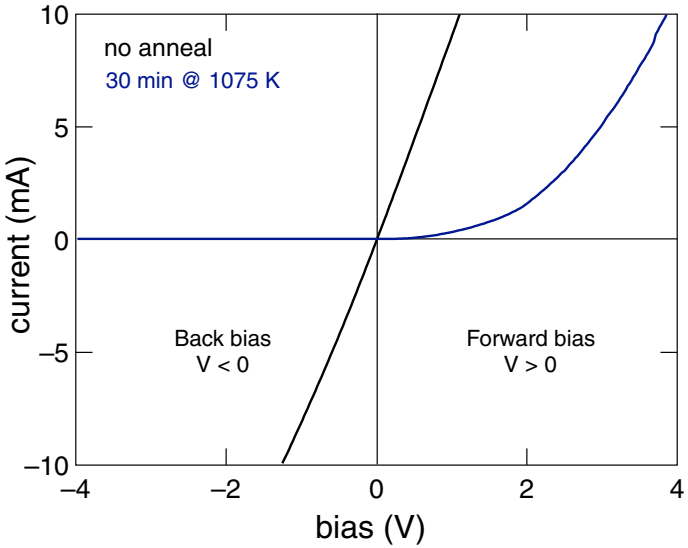

photon energy (eV)
3
2
1
0.5
1.0
0.8
0.6
0.4
0.2
0
absorptance
fs laser
doped silicon
sub-bandgap
IR absorption
silicon
substrate
0
1
2
3
wavelength (μm)


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)

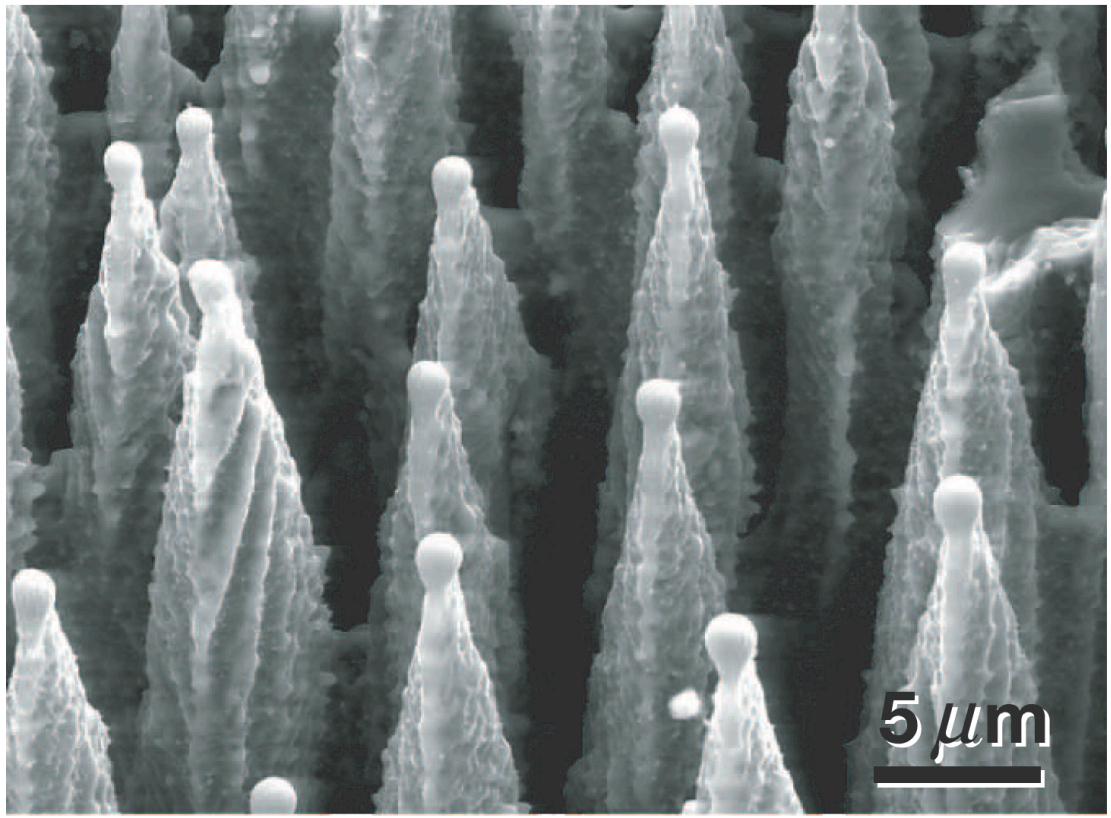
fs laser
Sulfur
compound

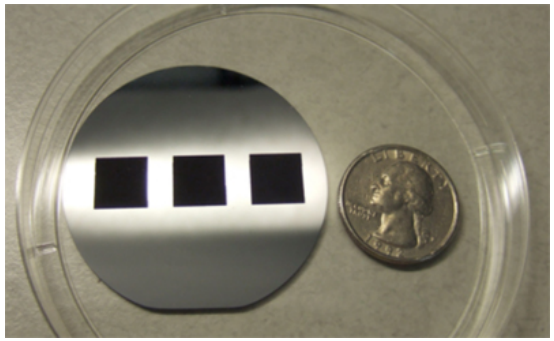


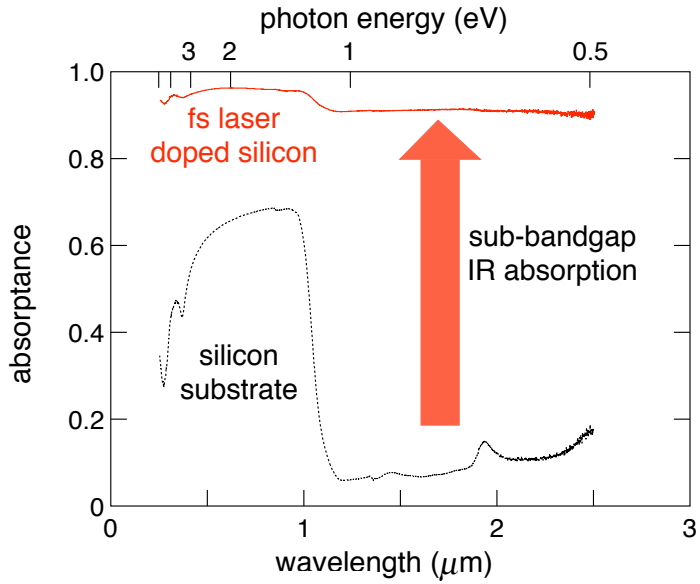

photon energy (eV)
3
2
1
0.5
1.0
0.8
0.6
0.4
0.2
0
absorptance
fs laser
doped silicon
sub-bandgap
IR absorption
silicon
substrate
0
1
2
3
wavelength (μm)

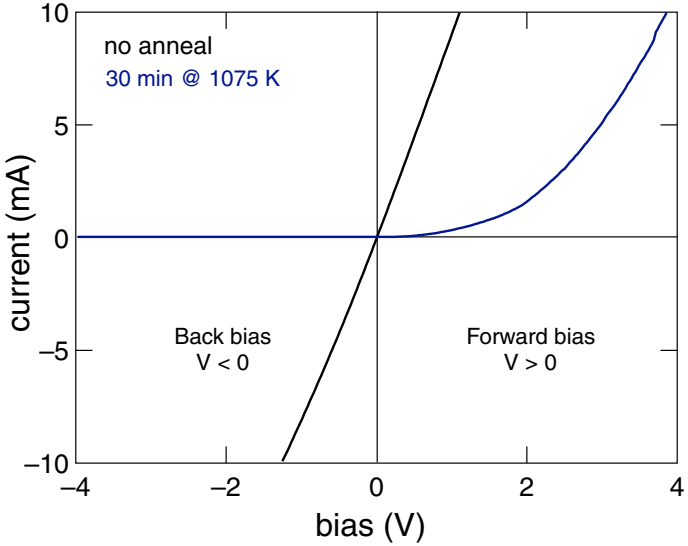

10
5
0
−5
−10
current (mA)
no anneal
30 min @ 1075 K
Back bias
V < 0
Forward bias
V > 0
−4
−2
0
2
4
bias (V)

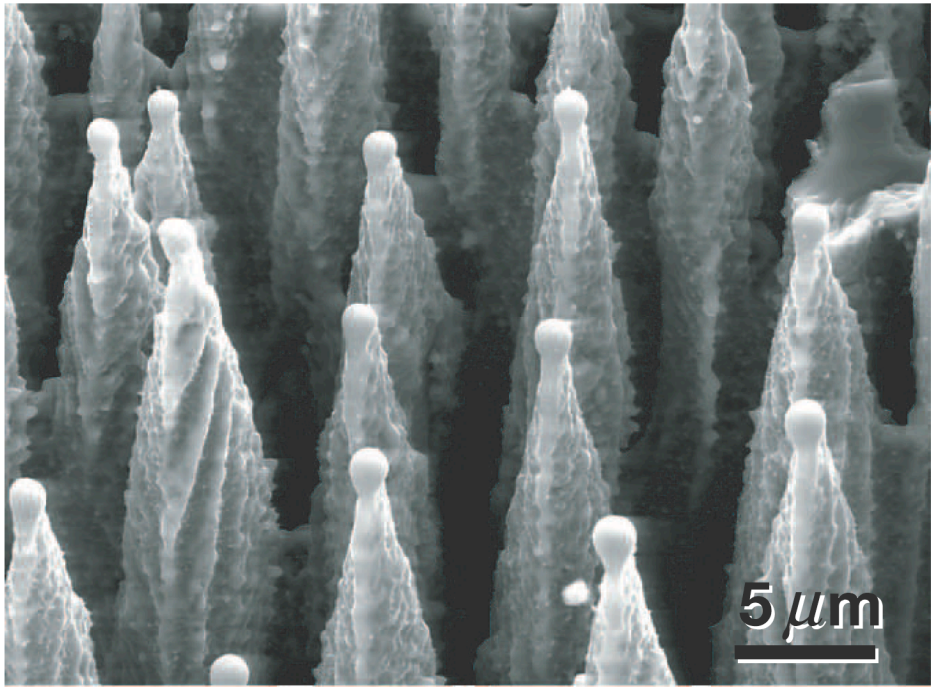
fs laser


5 μm

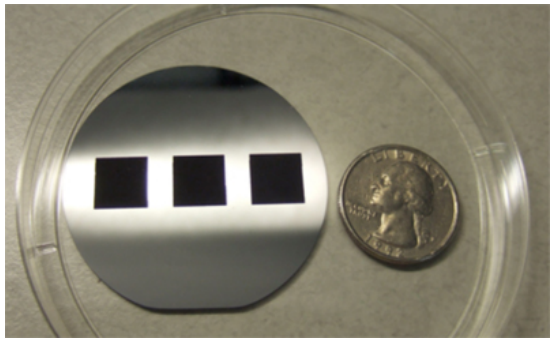


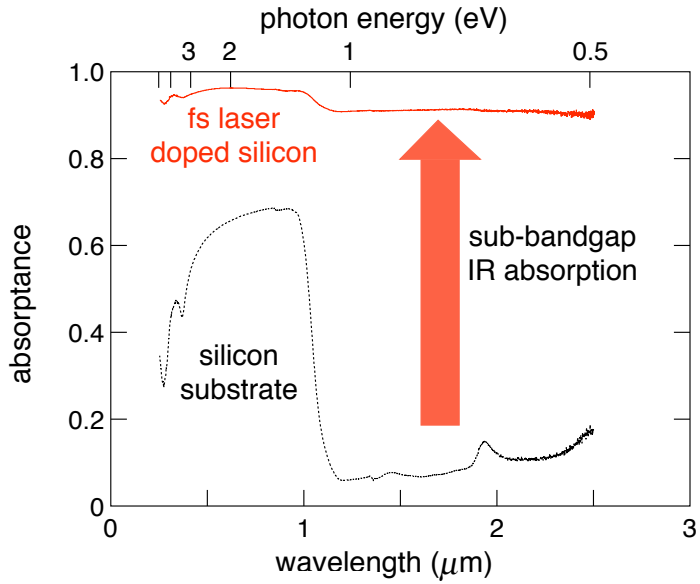

photon energy (eV)
3
2
1
0.5
1.0
0.8
0.6
0.4
0.2
0
absorptance
fs laser
doped silicon
sub-bandgap
IR absorption
silicon
substrate
0
1
2
3
wavelength (μm)

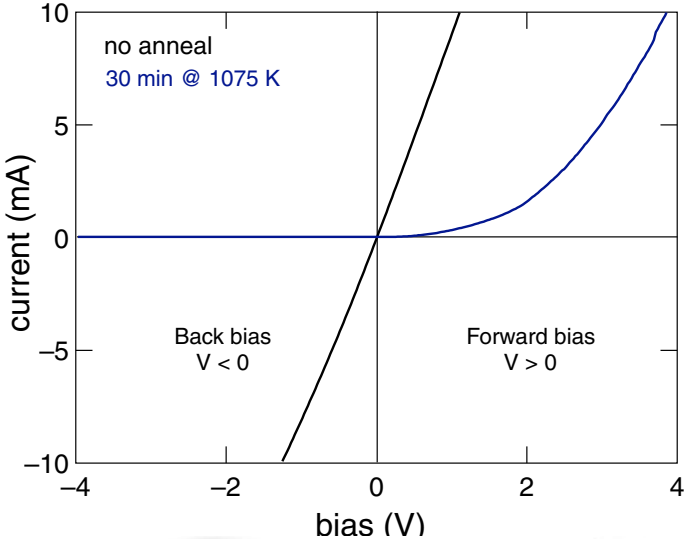

10
5
0
−5
−10
current (mA)
no anneal
30 min @ 1075 K
Back bias
V < 0
Forward bias
V > 0
−4
−2
0
2
4
bias (V)

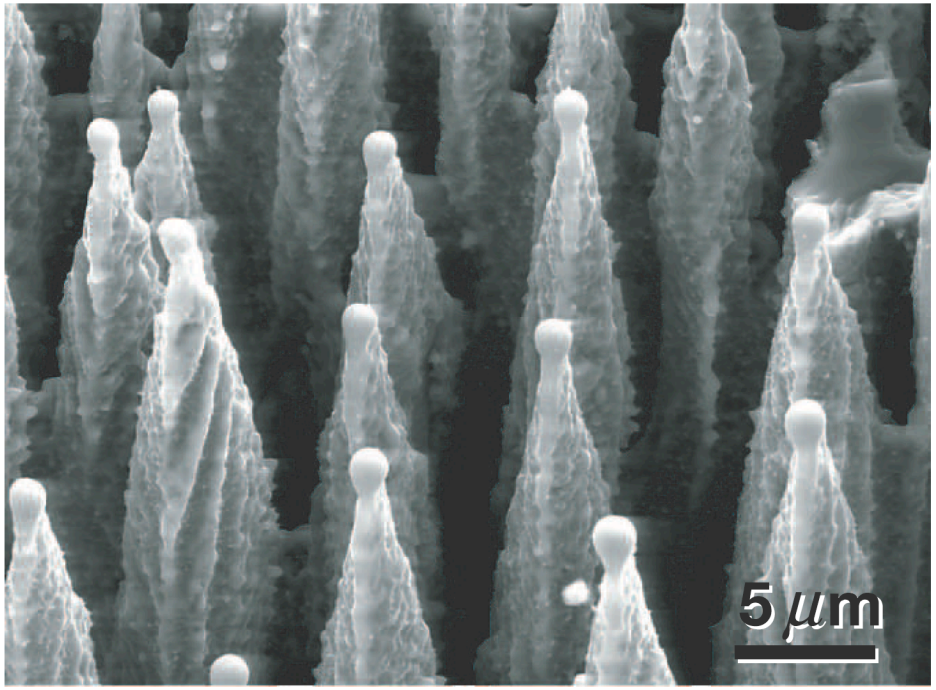

5 μm

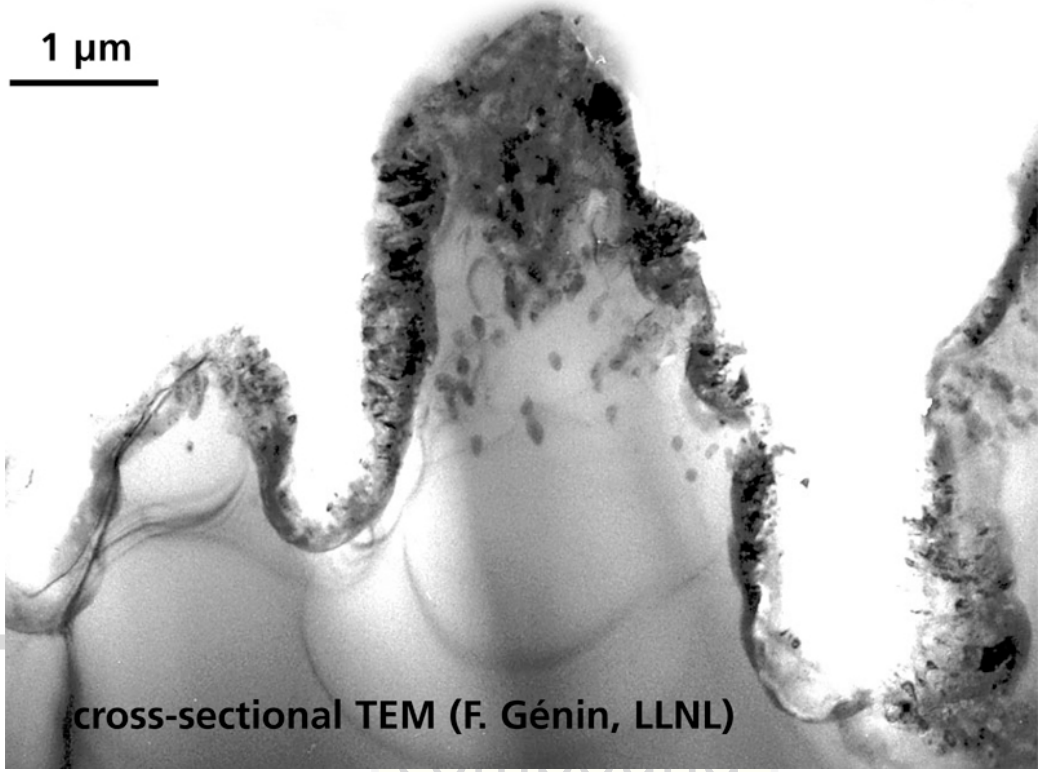
Sulfur
compound

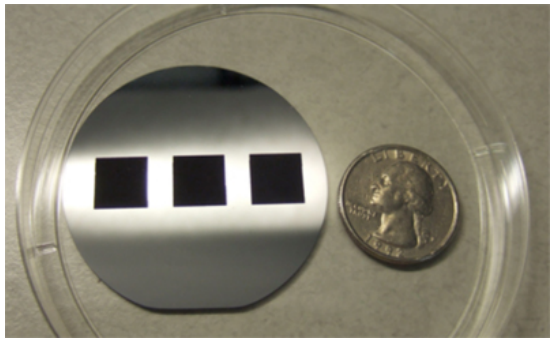


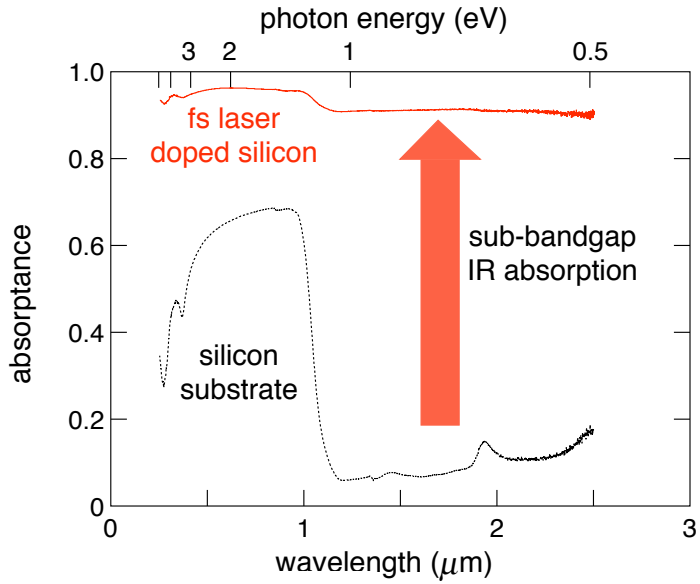

photon energy (eV)
3
2
1
0.5
1.0
0.8
0.6
0.4
0.2
0
absorptance
fs laser
doped silicon
sub-bandgap
IR absorption
silicon
substrate
0
1
2
3
wavelength (μm)

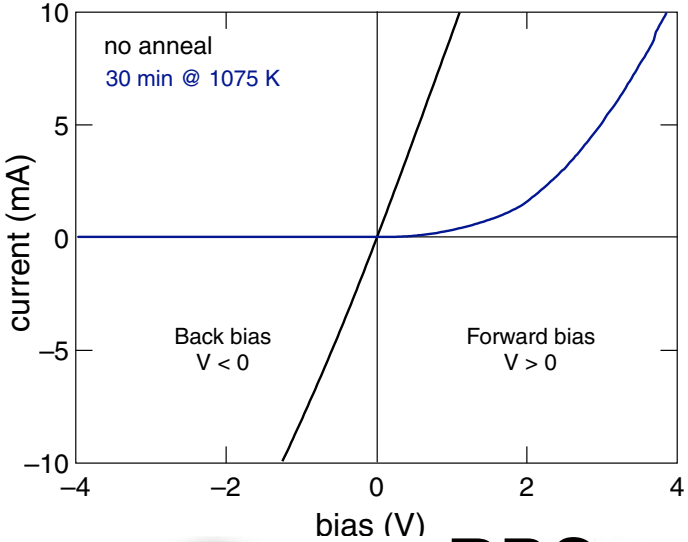

10
5
0
−5
−10
current (mA)
no anneal
30 min @ 1075 K
Back bias
V < 0
Forward bias
V > 0
−4
−2
0
2
4
bias (V)

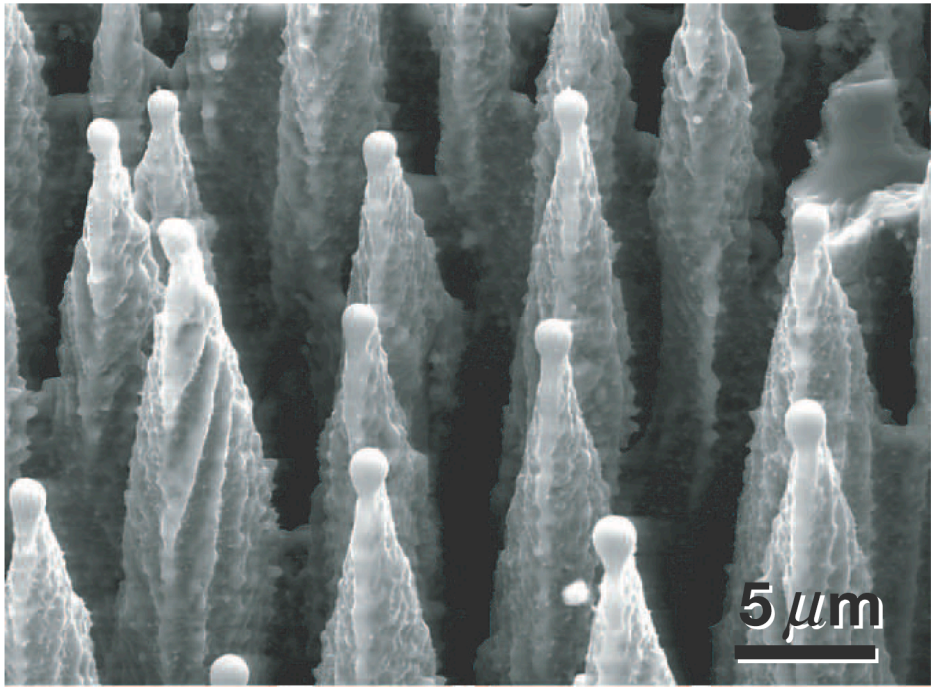

5 μm

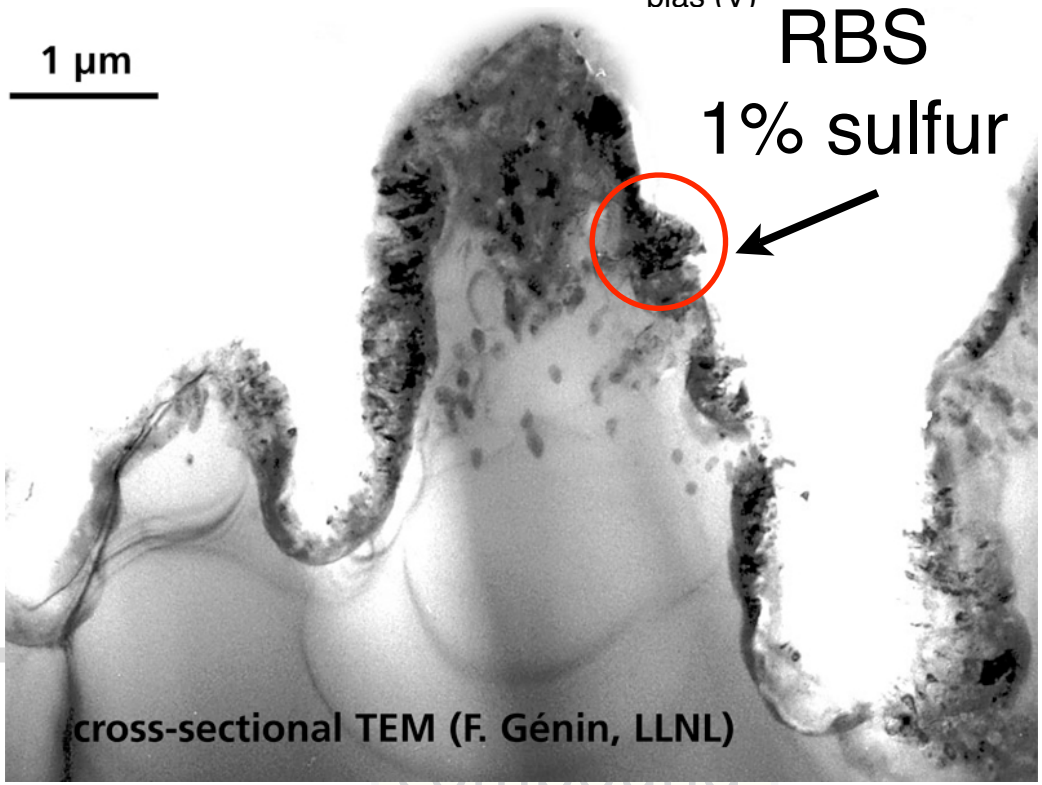

1 μm
cross-sectional TEM (F. Génin, LLNL)

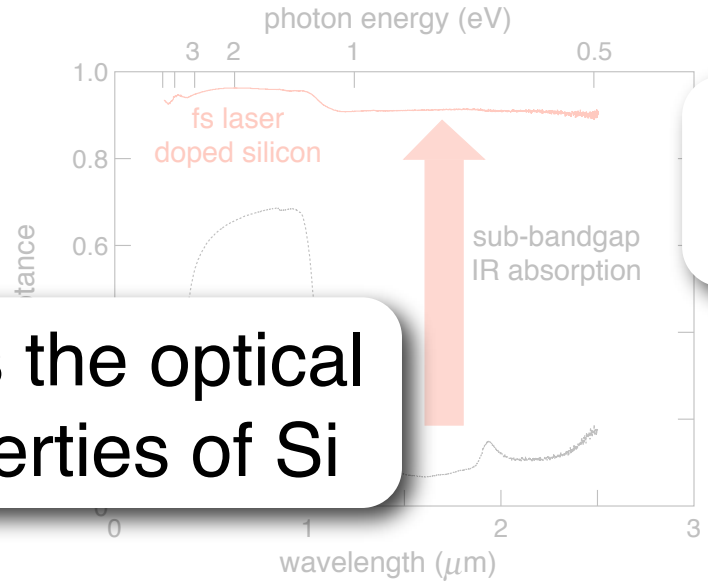



photon energy (eV)
3
2
1
0.5
1.0
0.8
0.6
0.4
0.2
0
absorptance
fs laser
doped silicon
sub-bandgap
IR absorption
silicon
substrate
0
1
2
3
wavelength (μm)

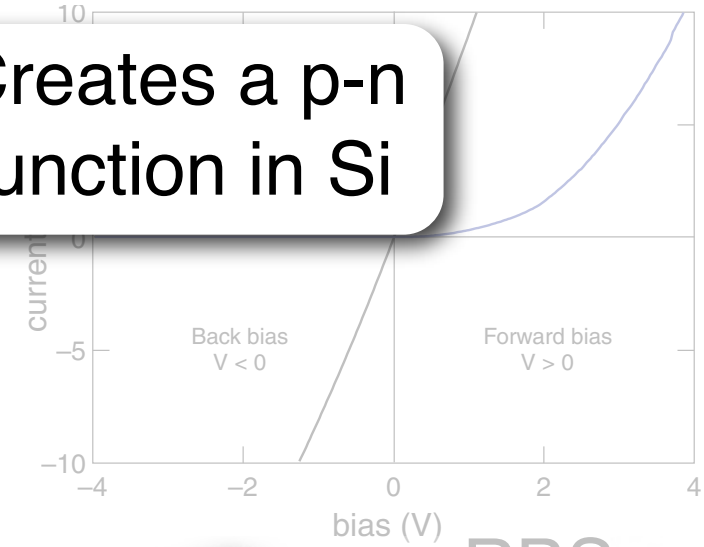

10
5
0
−5
−10
current (mA)
no anneal
30 min @ 1075 K
Back bias
V < 0
Forward bias
V > 0
−4
−2
0
2
4
bias (V)


5 μm

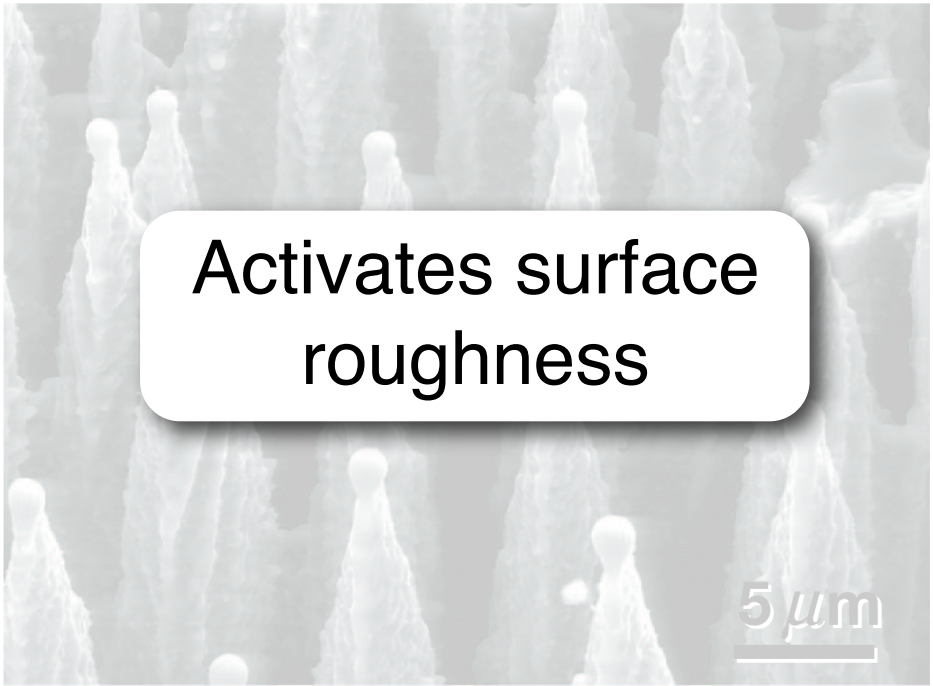

1 μm
RBS
1% sulfur
cross-sectional TEM (F. Génin, LLNL)



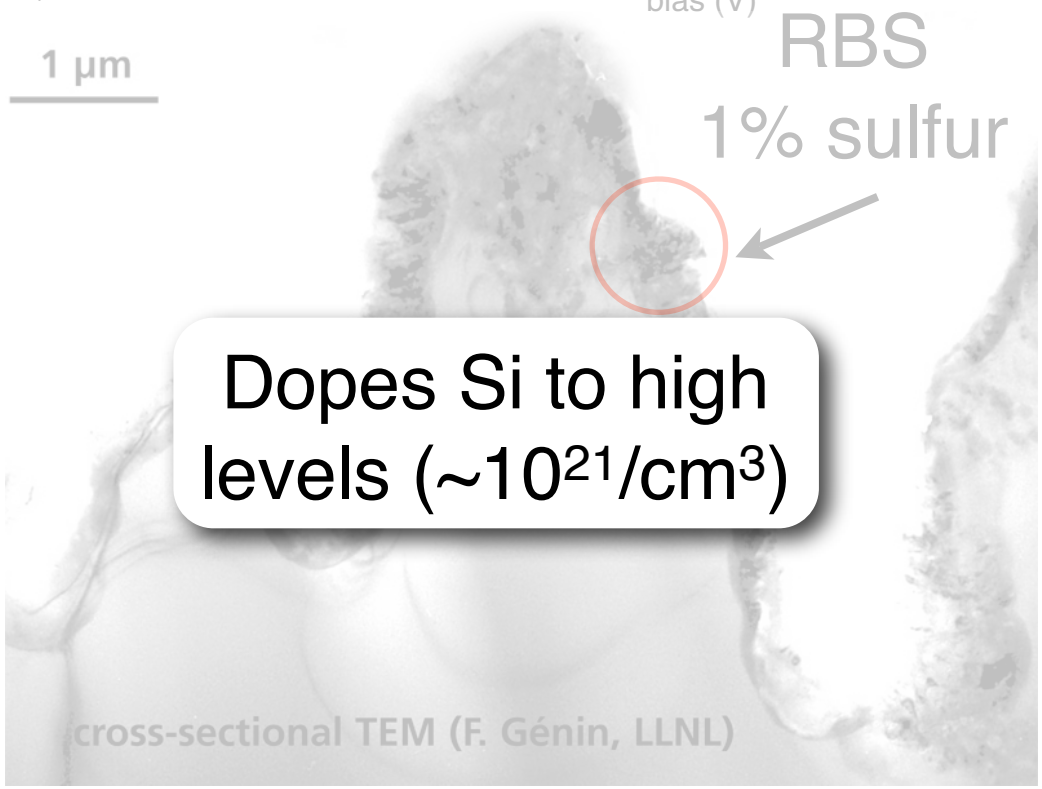
Alters the optical properties of Si



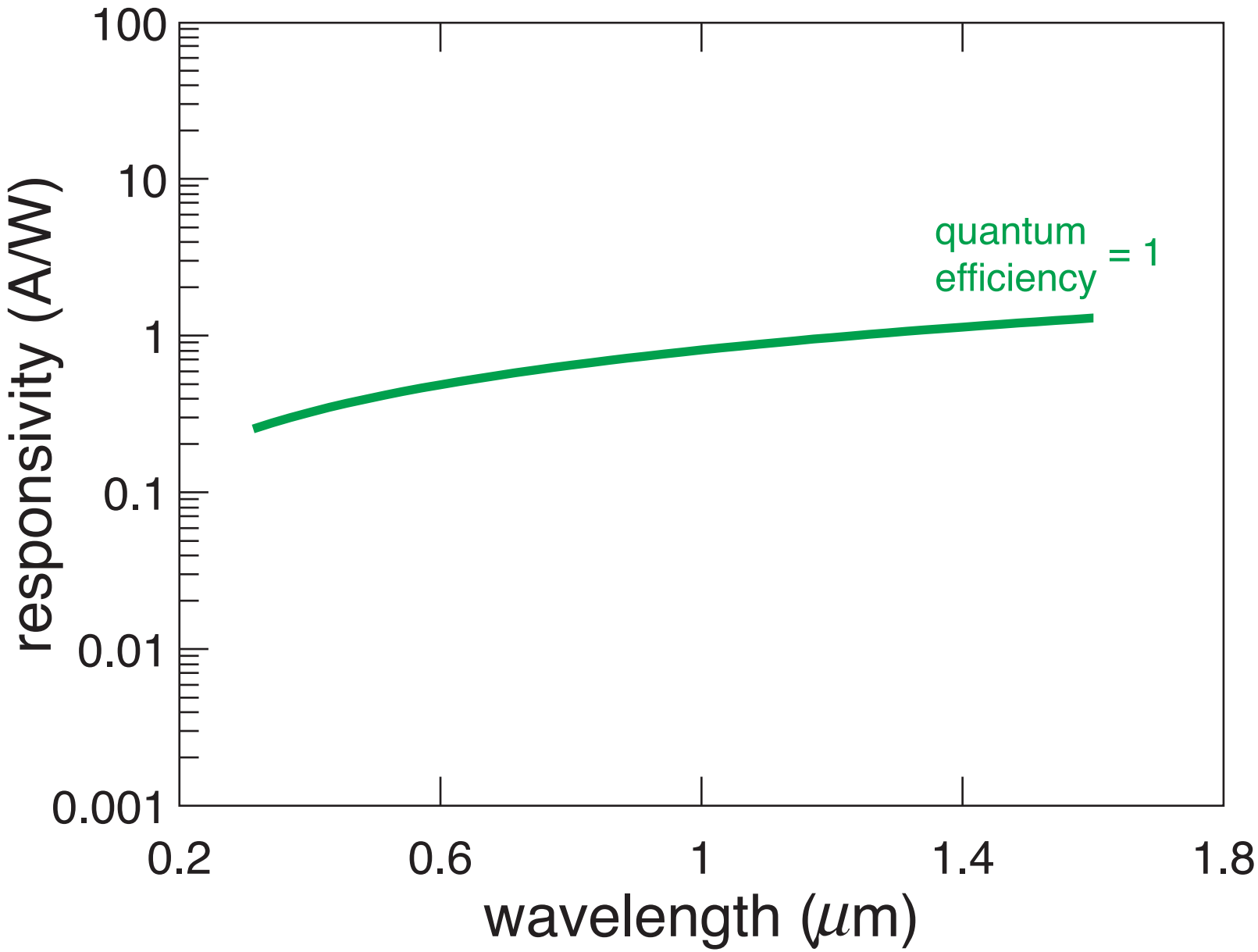
Creates a p-n junction in Si

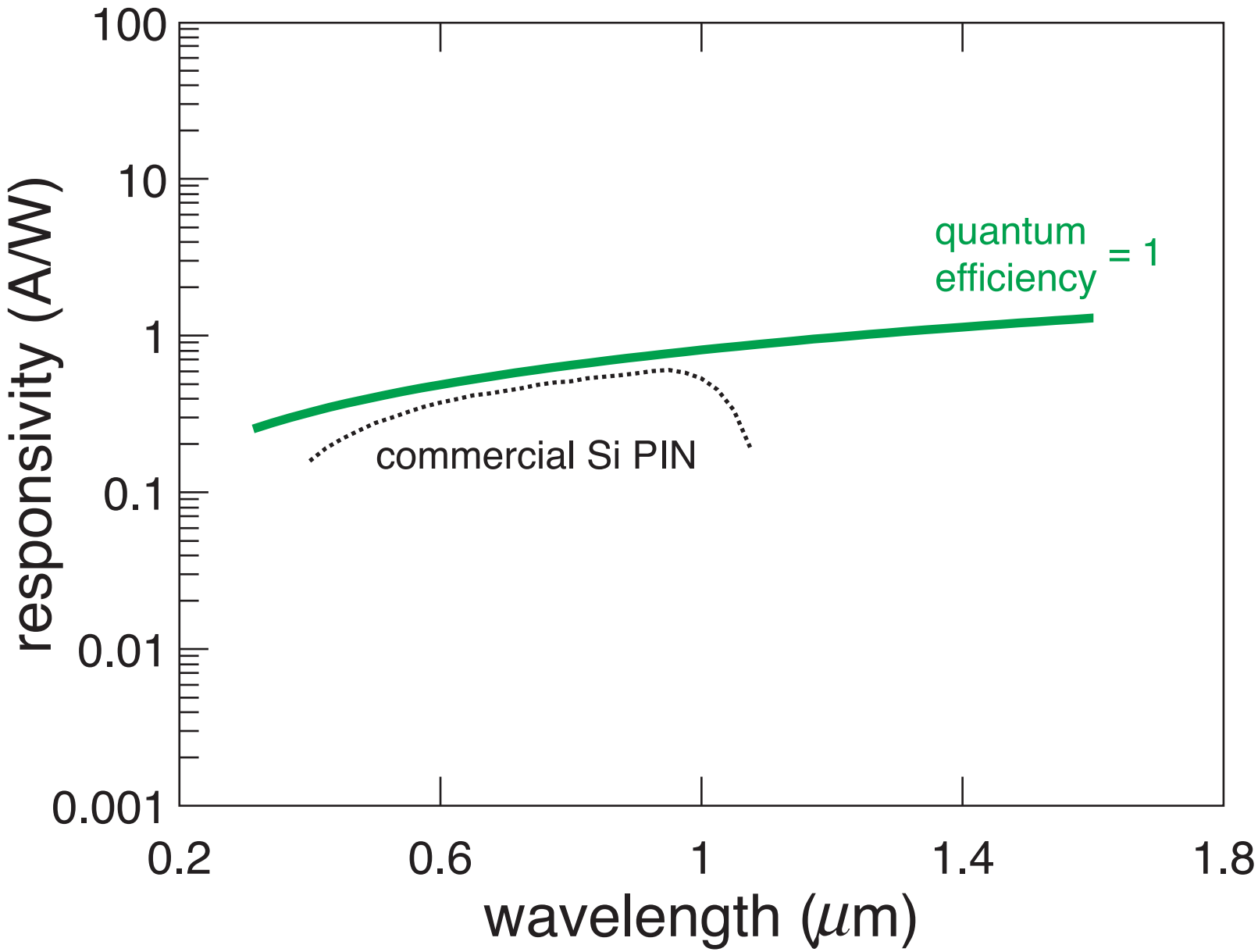


Activates surface roughness

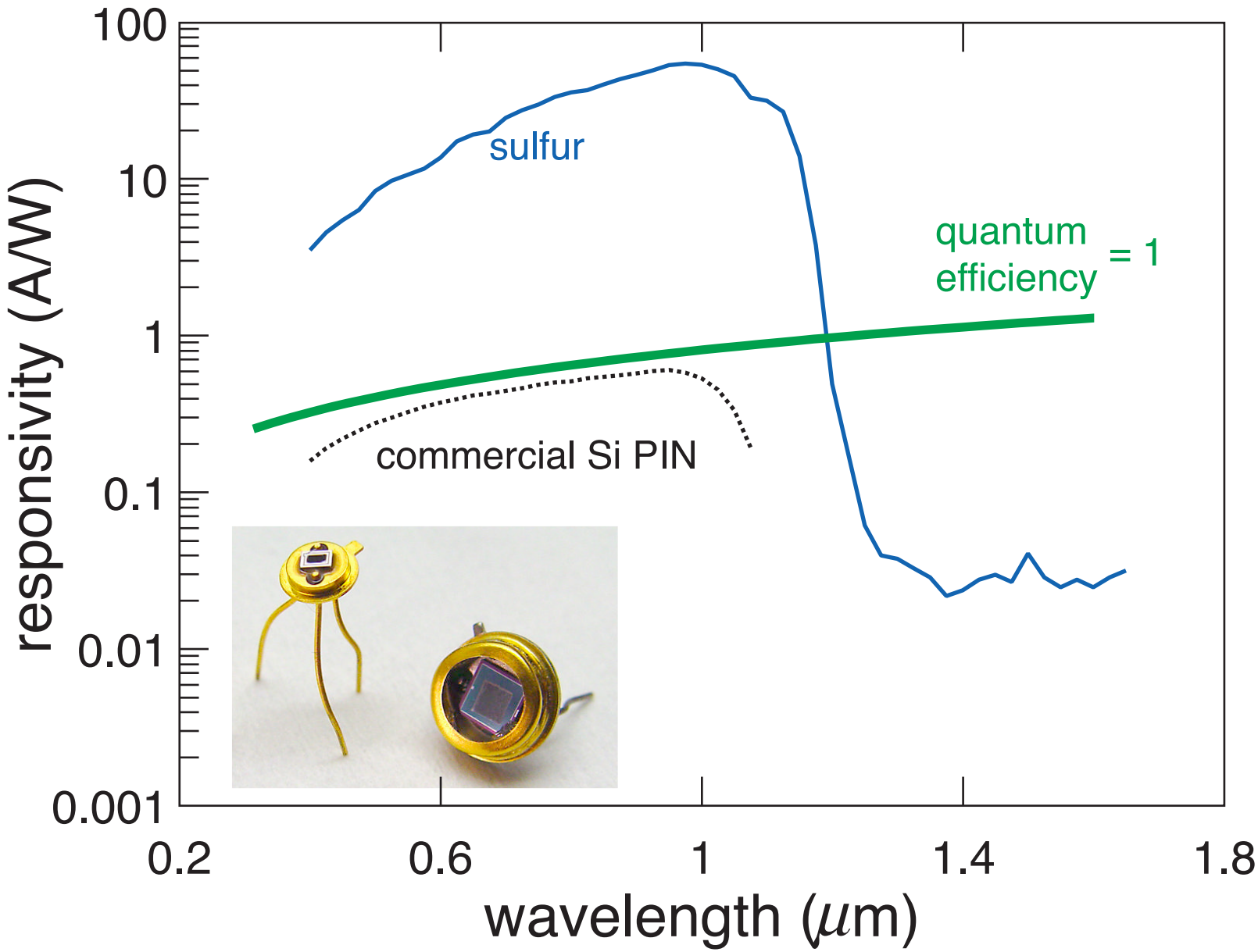


Dopes Si to high levels (~$10^{21}/cm^3$)

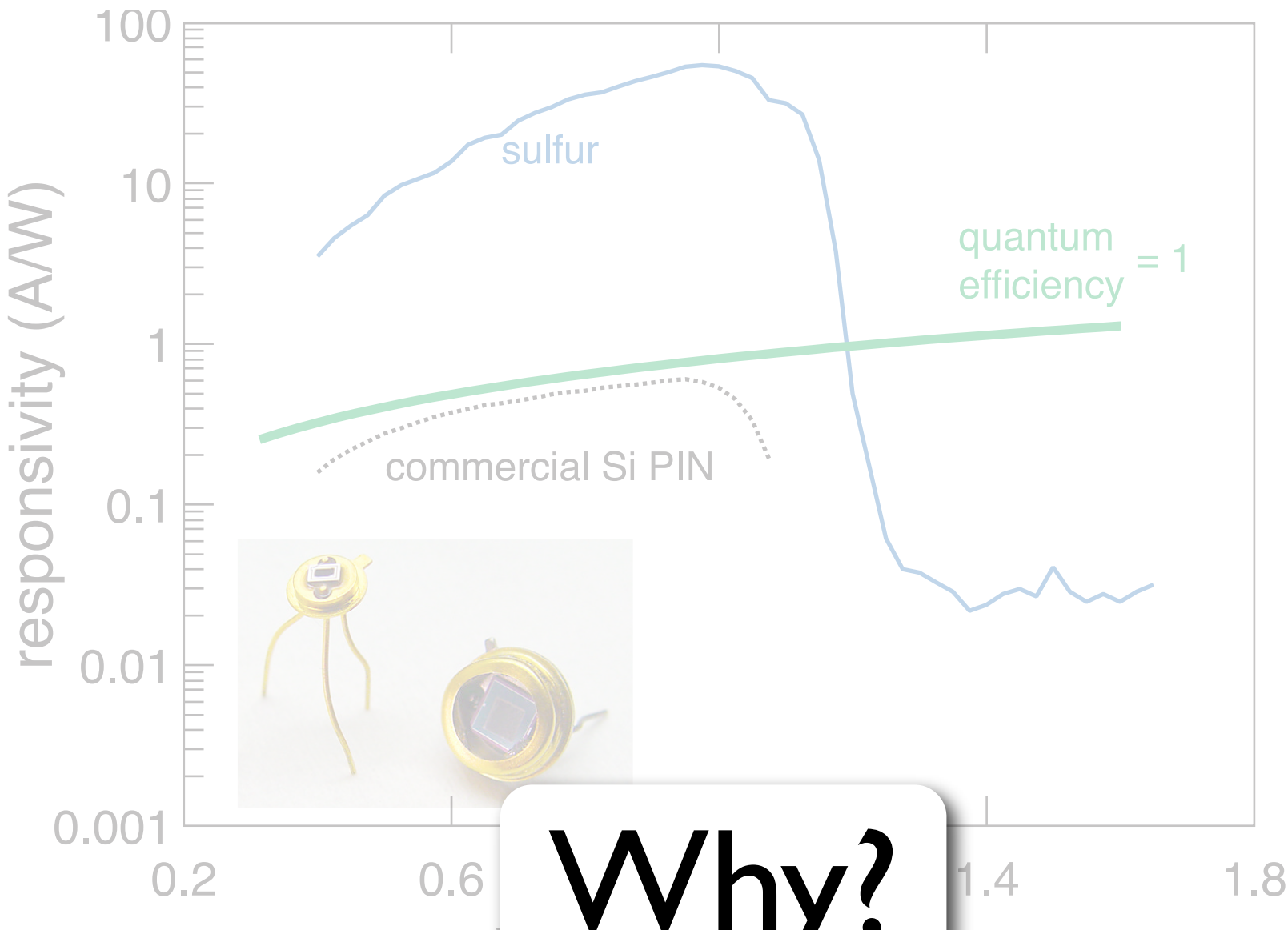

100
10
1
0.1
0.01
0.001
responsivity (A/W)
quantum
efficiency
= 1
0.2
0.6
1
1.4
1.8
wavelength (μm)


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?

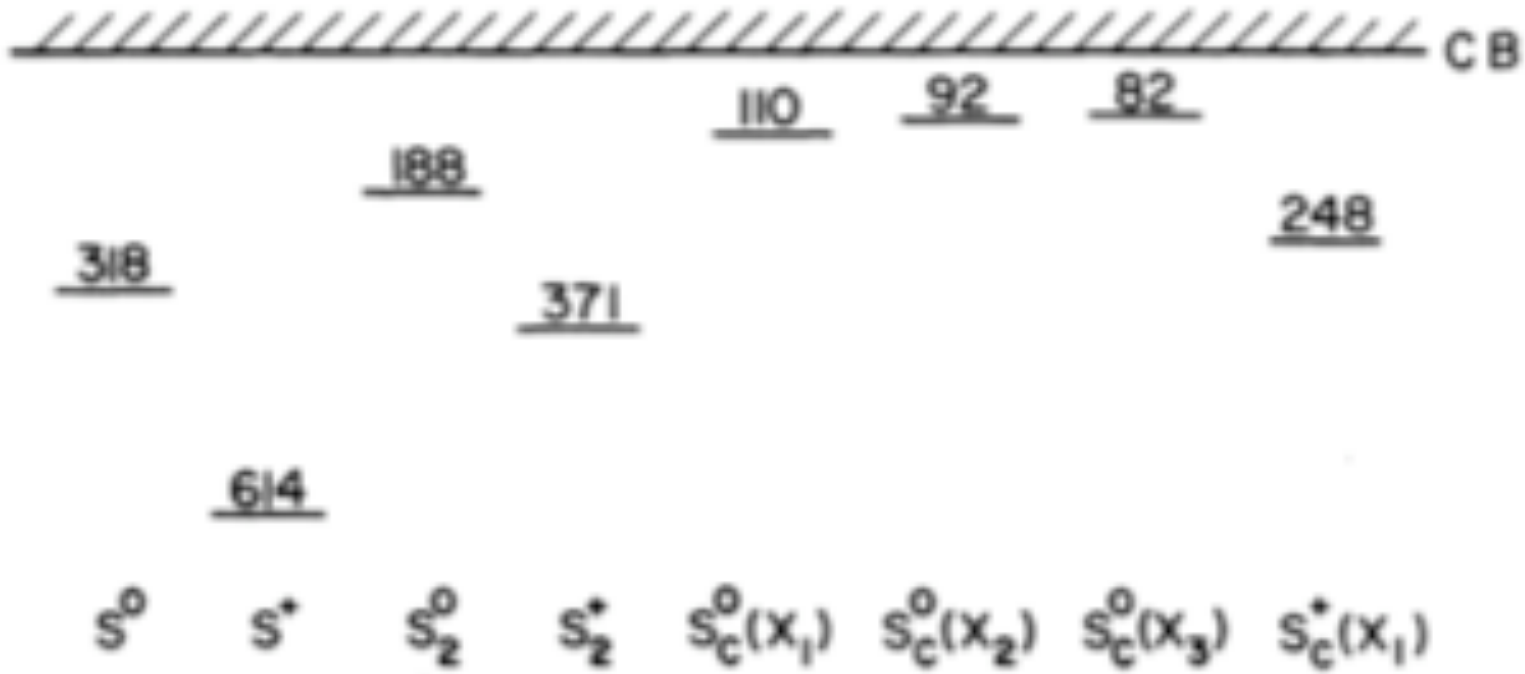


FIG. 1. Sulfur-related centers in silicon. $S_c^+(X_1)$, $S_c^0(X_2)$, and $S_c^0(X_3)$ are sulfur-related complexes not observed previously (see also, however, Refs. 29 and 30). The binding energies of all centers are taken from this paper and are similar to those found in the literature (Refs. 8, 15, 22, 23, 25, 30, 31, and 37—44).