Mid-infrared absorptance of silicon hyperdoped with chalcogens via fs-laser irradiation

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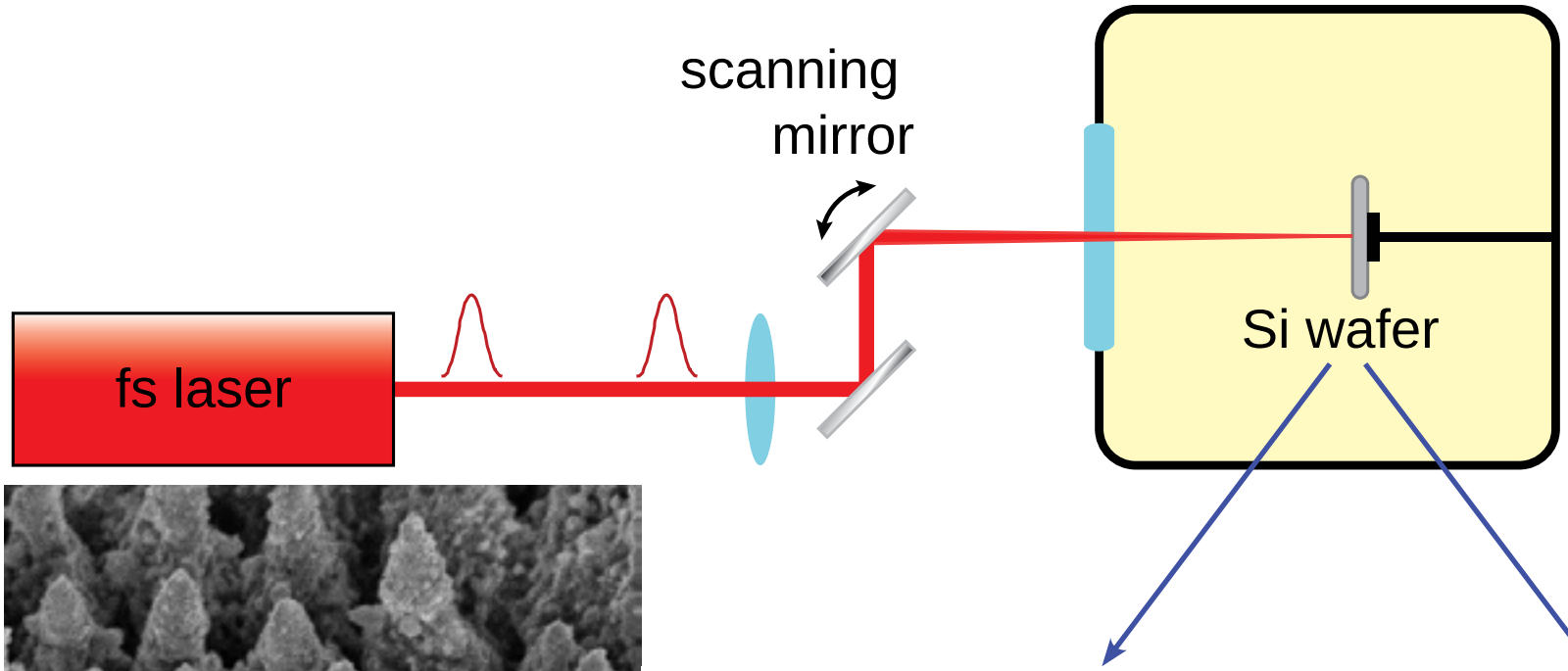
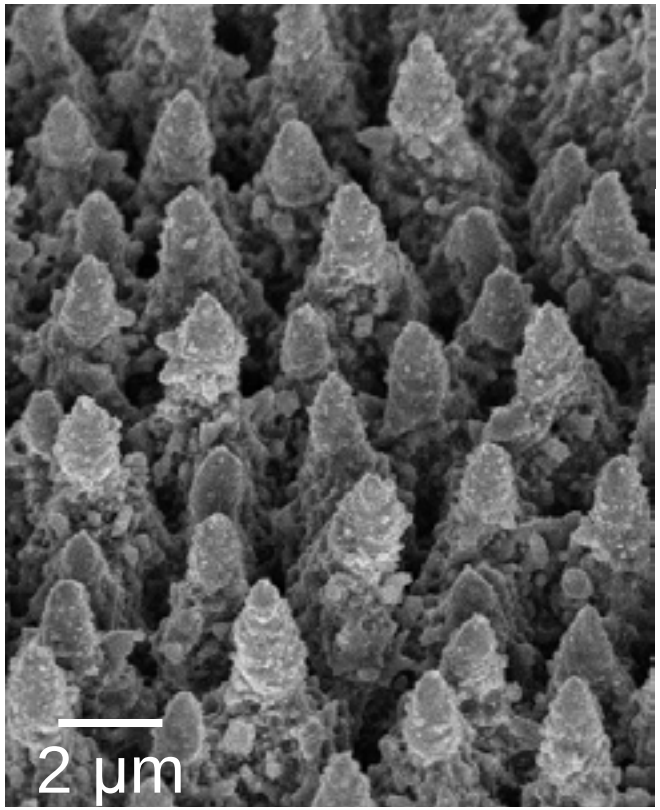
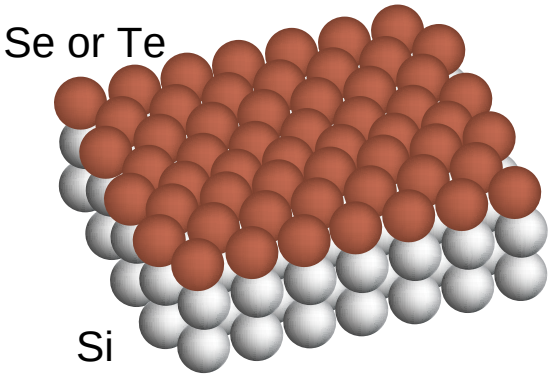
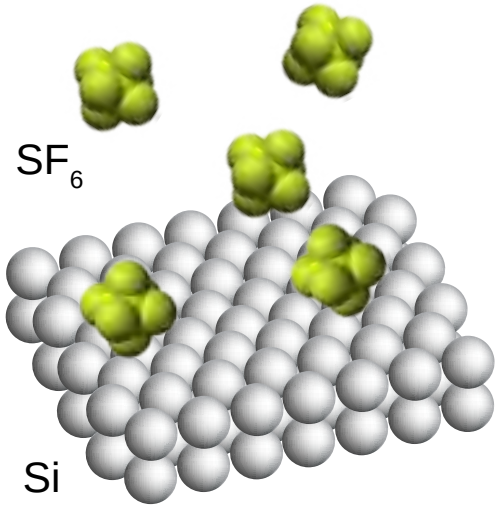
Introduction

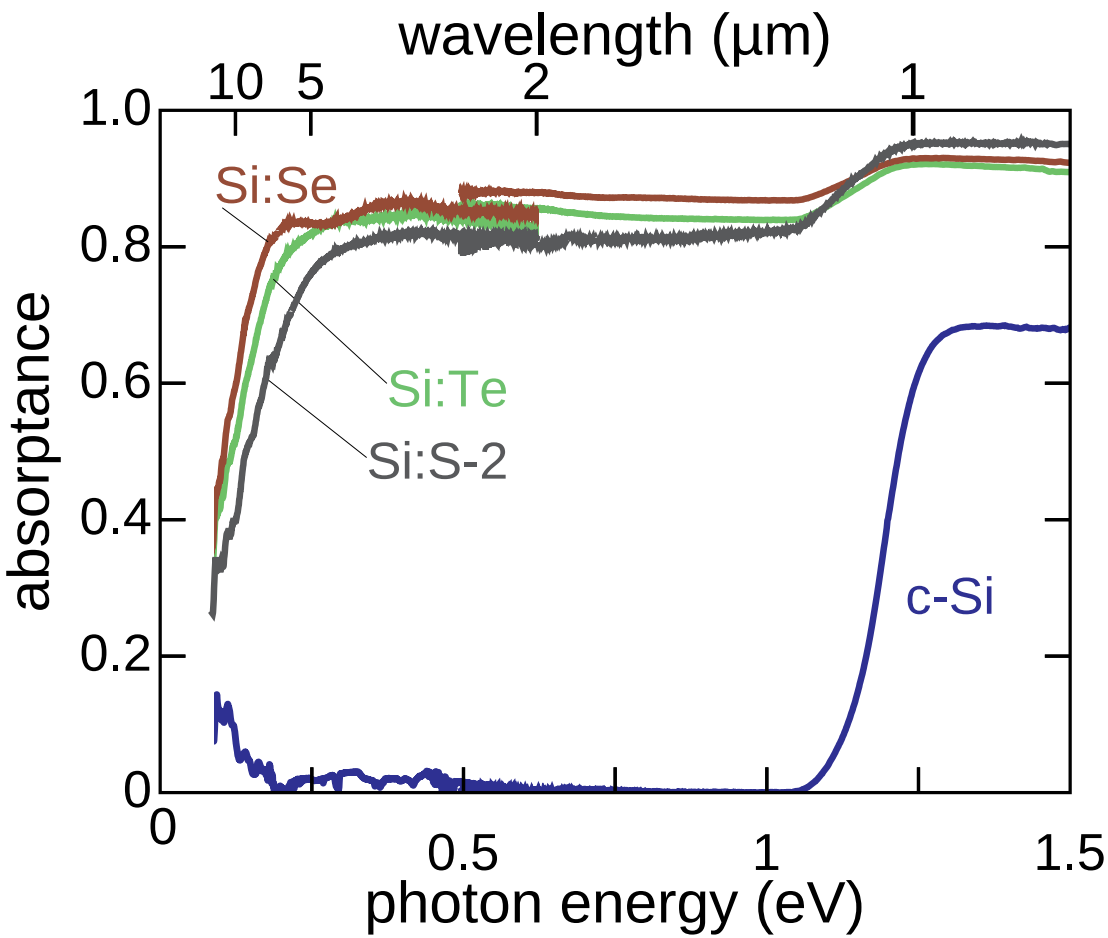








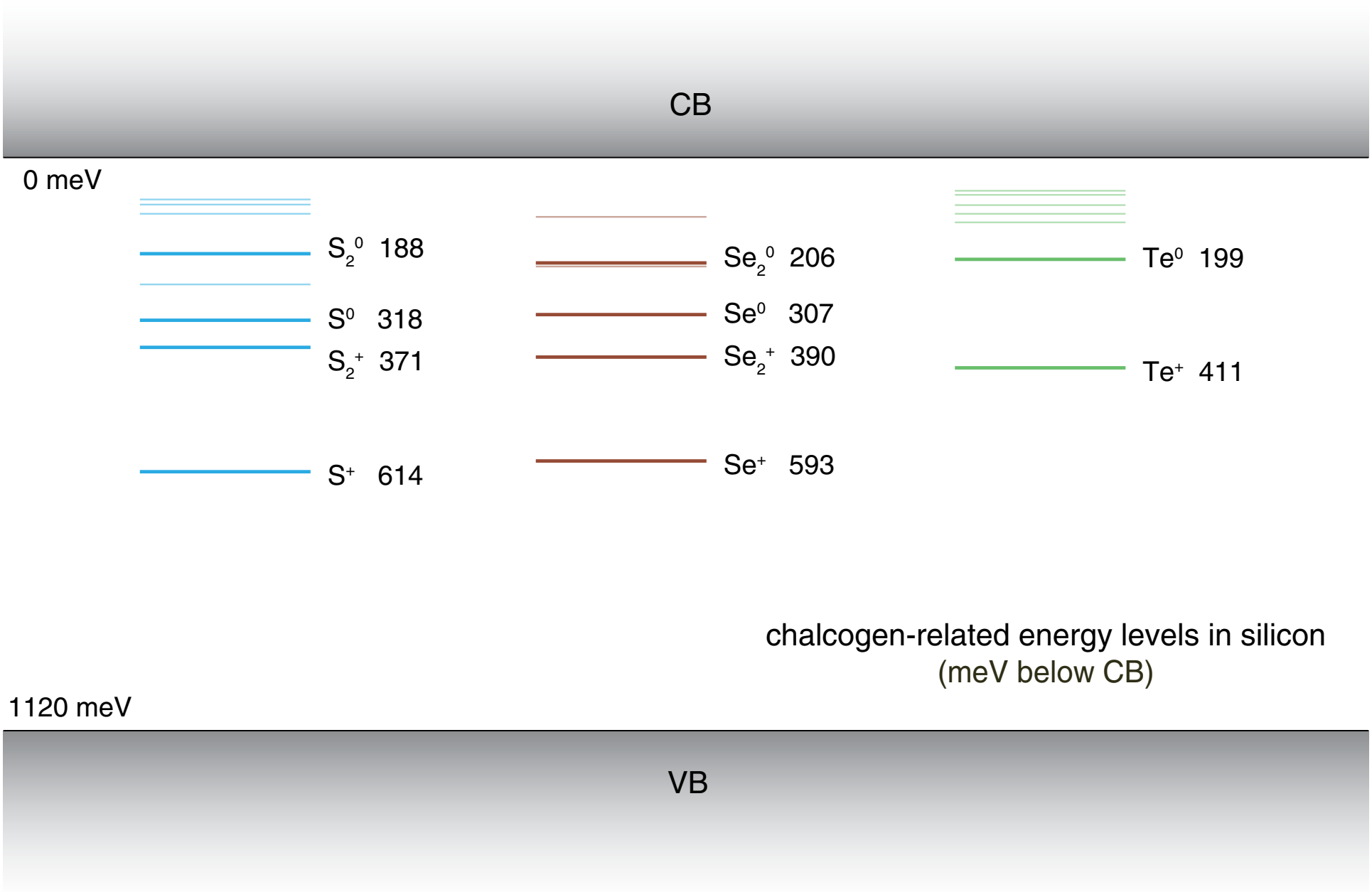
Introduction



- Mid-IR absorption
- light–matter interaction
- annealing and
  free carrier absorption

Mid-IR absorption

at low concentration

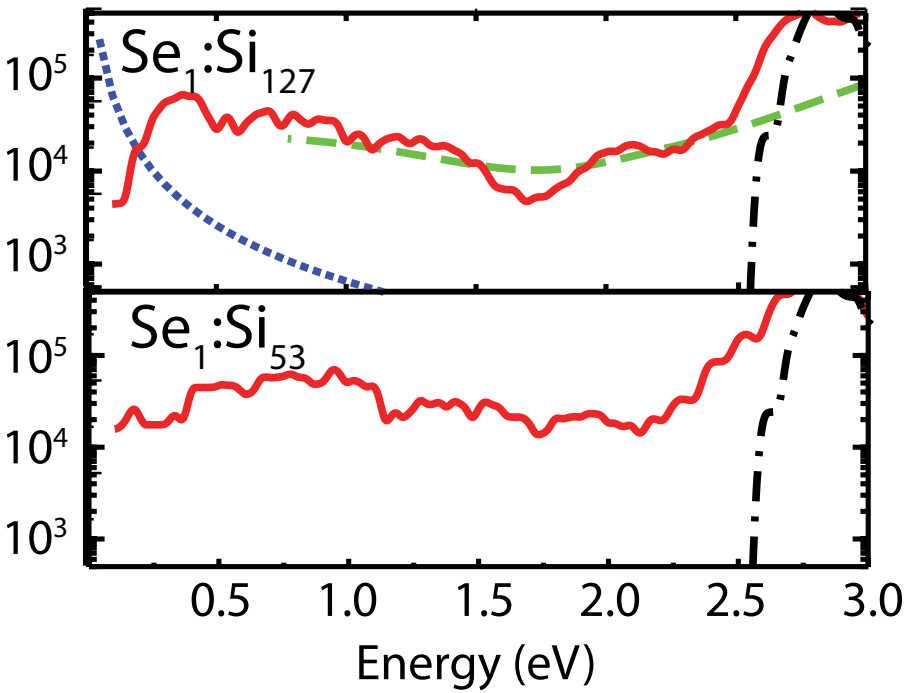


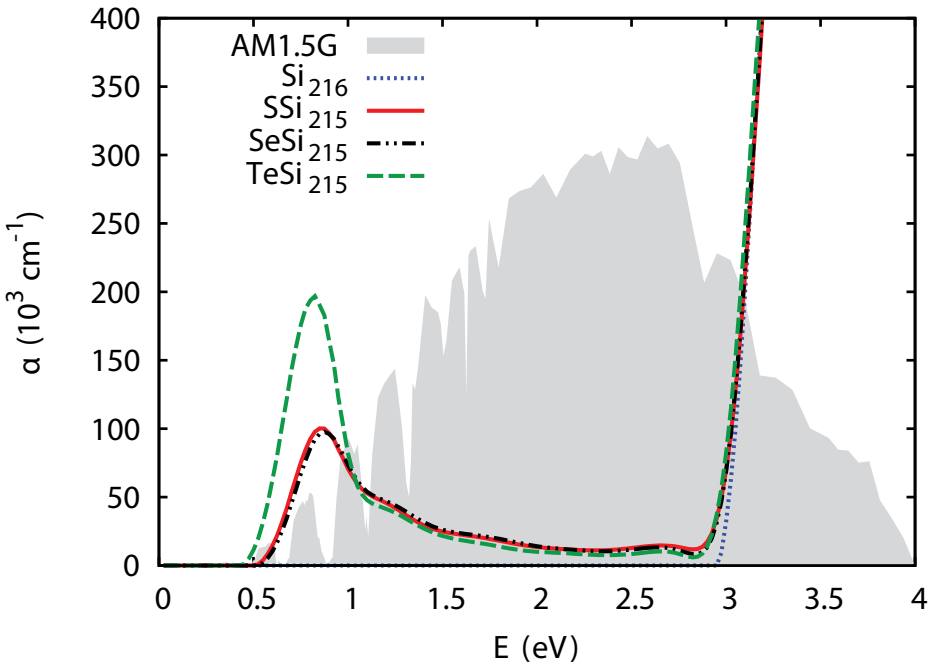
chalcogen-related energy levels in silicon
(meV below CB)

Mid-IR absorption

at high concentration

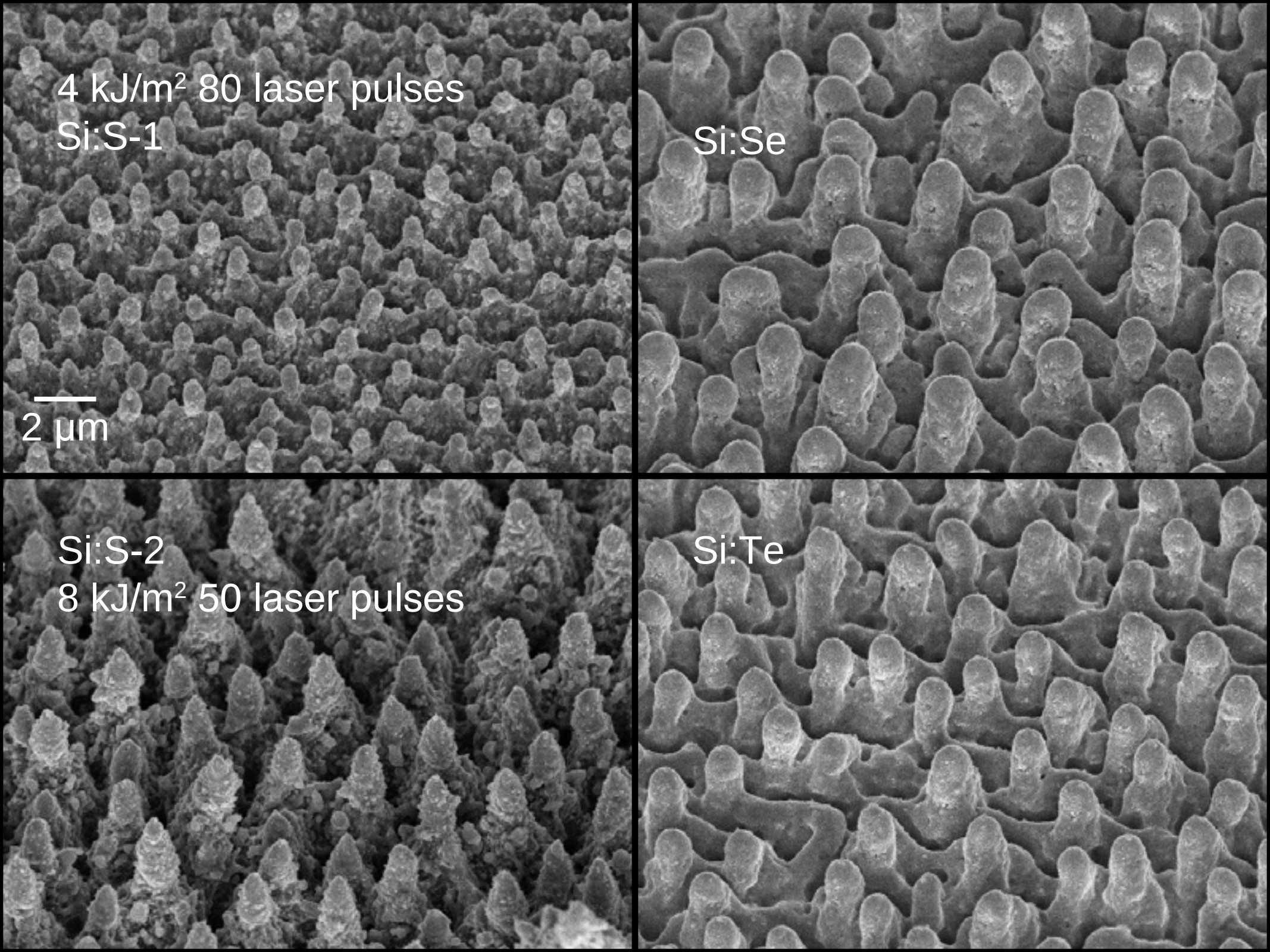
absorption coefficients





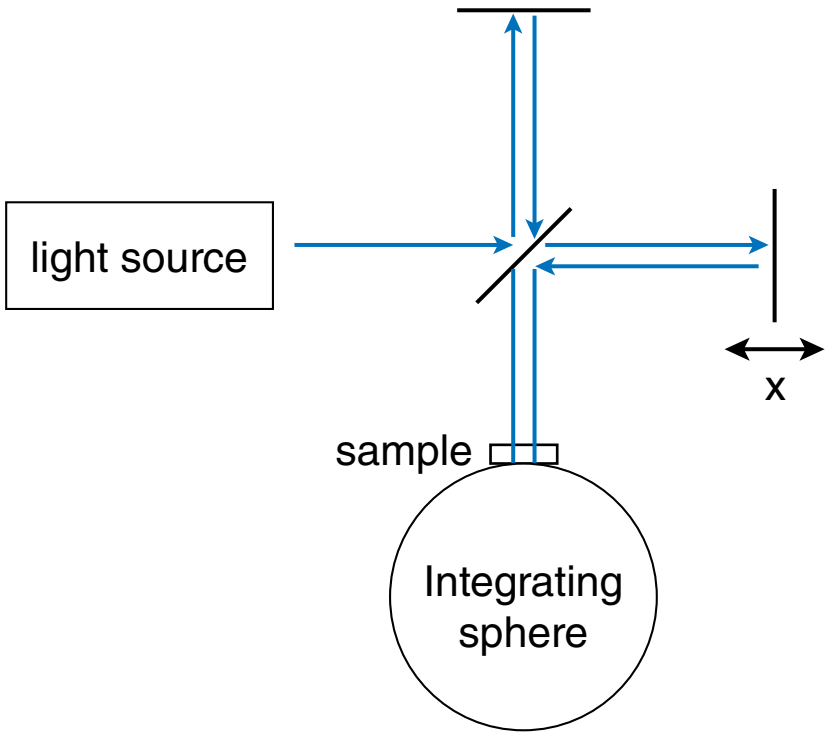
- pure Si
- Se:Si
- free carrier absorption
- Pan *et al.*, 2011

Sánchez *et al.*, PRB 82, 165201(2010)
Ertekin *et al.*, PRL 108, 026401 (2012)


4 kJ/m² 80 laser pulses
Si:S-1
2 µm
Si:Se
Si:S-2
8 kJ/m² 50 laser pulses
Si:Te

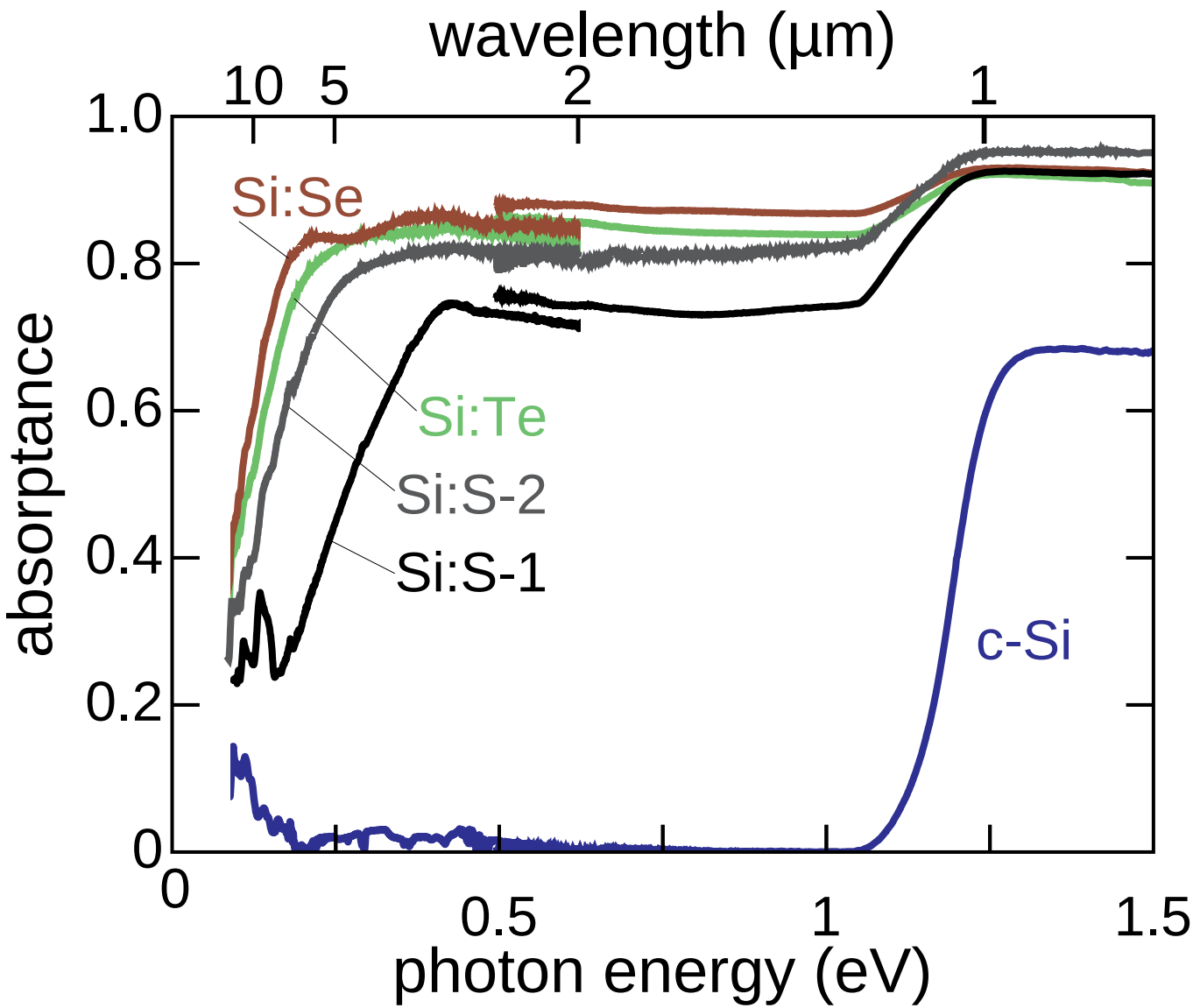
Mid-IR absorption

FTIR



$$A = 1 - R - T$$

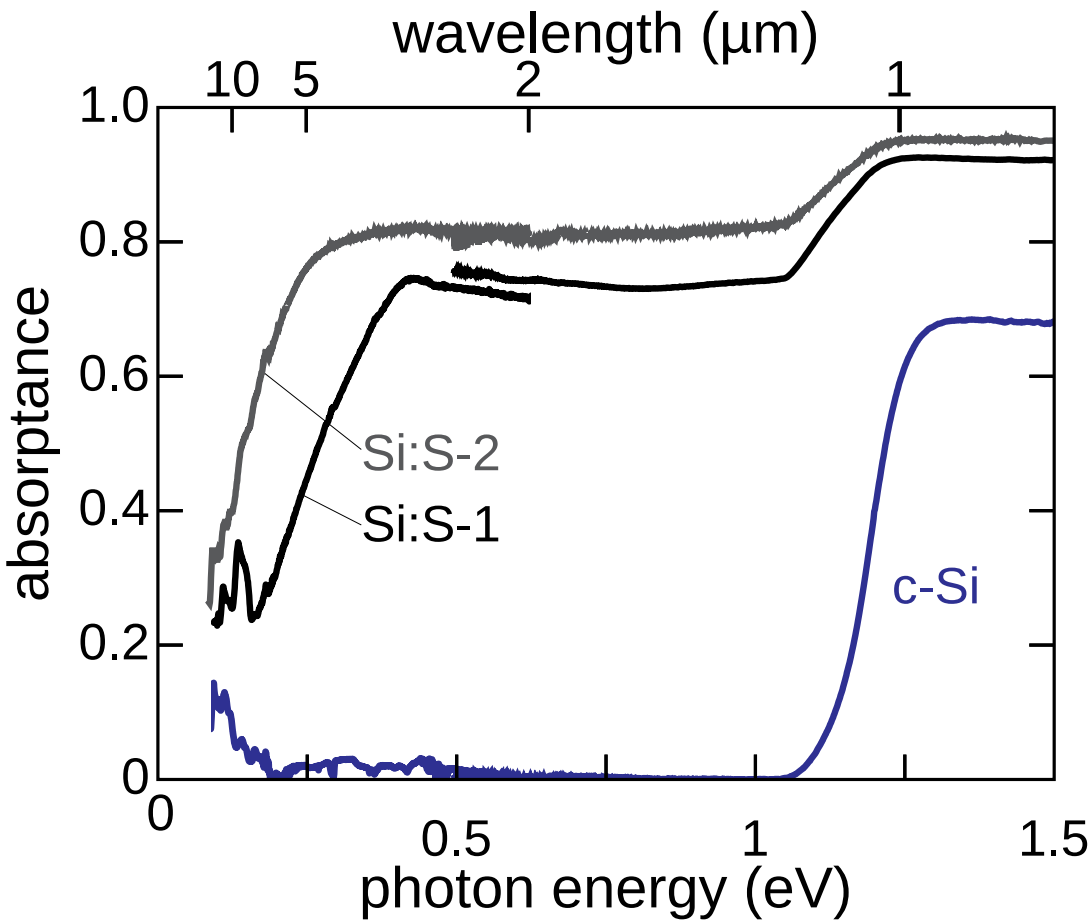
Mid-IR absorption

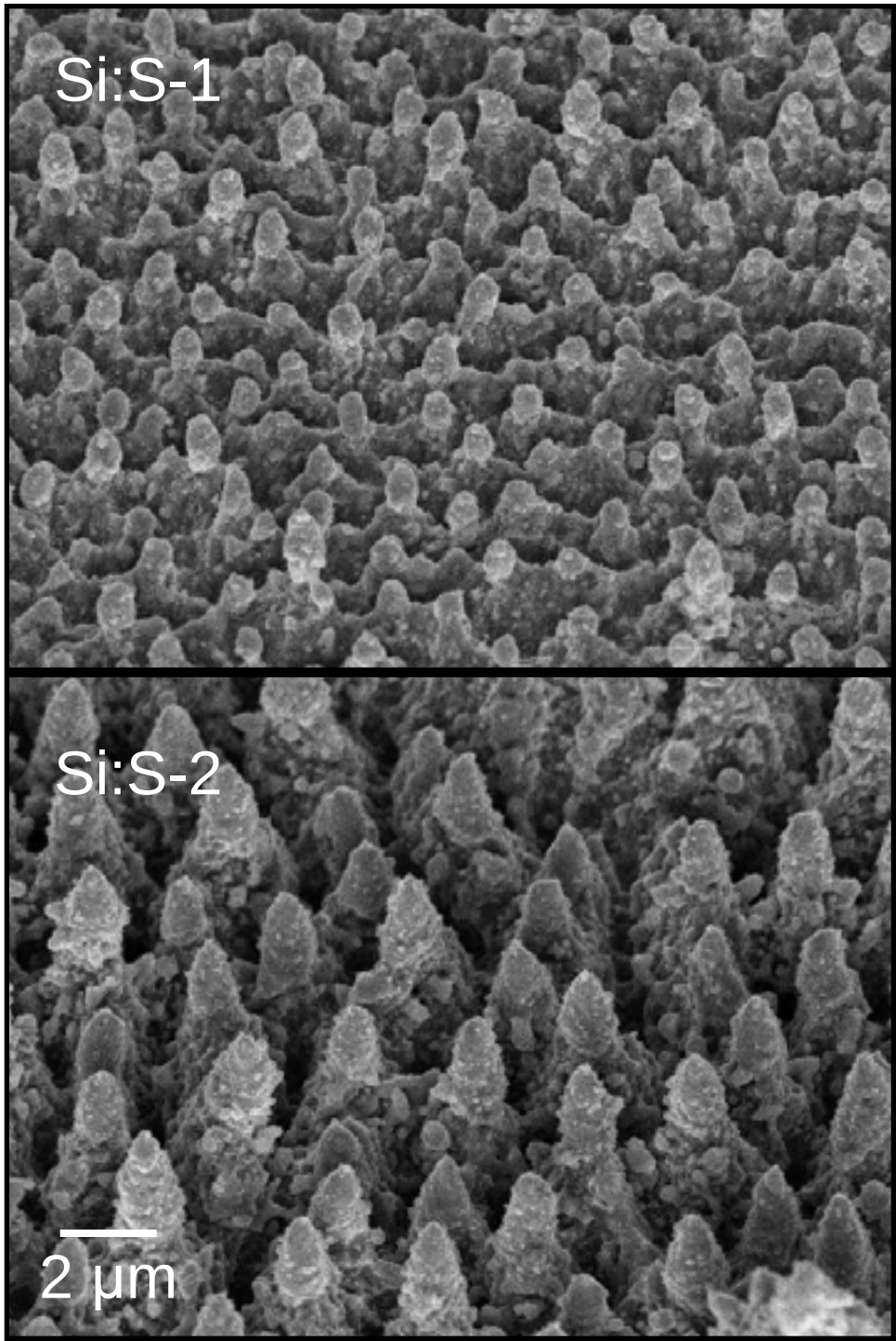


Outline

- Mid-IR absorption
- light–matter interaction
- annealing and free carrier absorption

Light–matter interaction



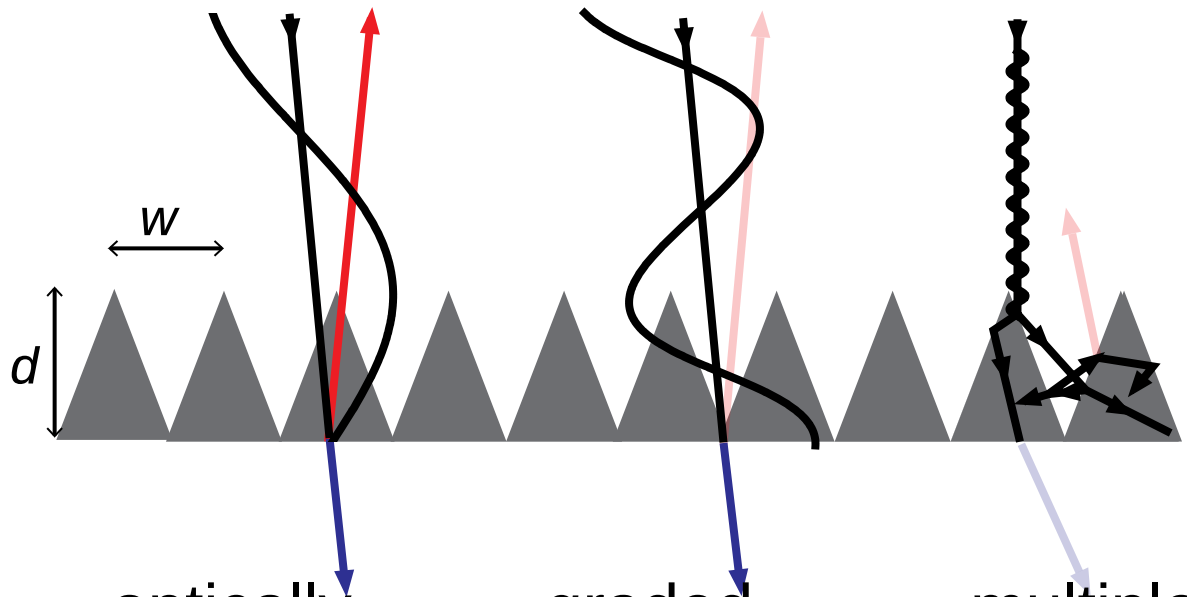


Light–matter interaction

λ = 20 μm λ = 10 μm λ = 1 μm

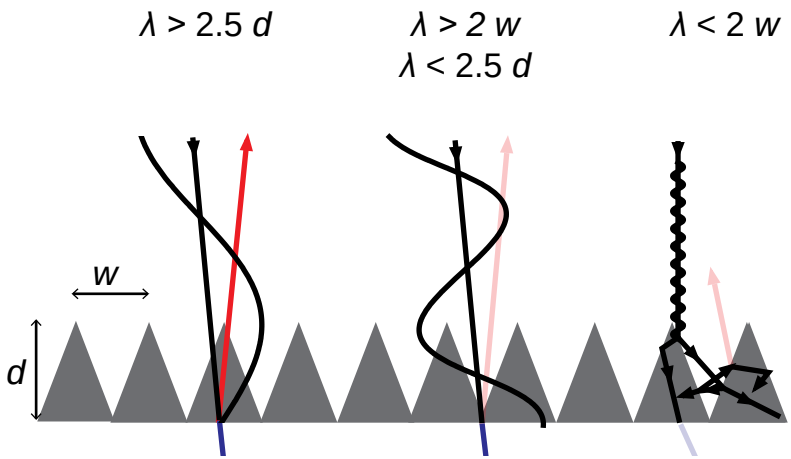
$\lambda > 2.5\,d$ $\lambda > 2\,w$, $\lambda < 2.5\,d$ $\lambda < 2\,w$

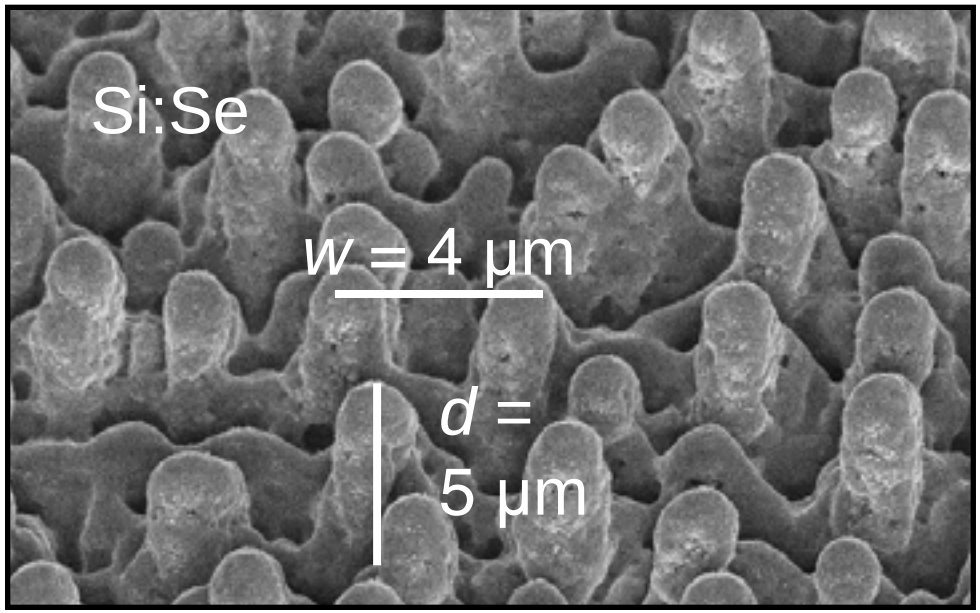
w = 4 μm
d = 5 μm

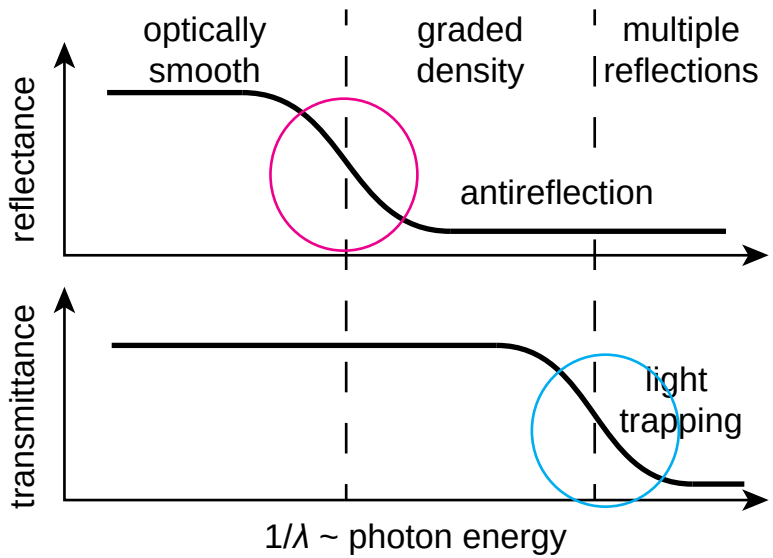


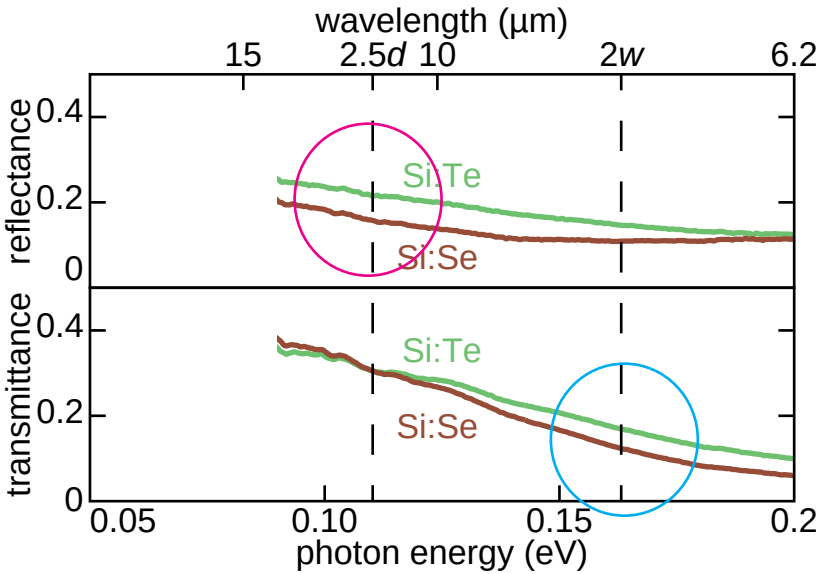
optically smooth	graded density	multiple reflections
R –	R ↓	R ↓
path length –	path length –	path length ↑

Light–matter interaction

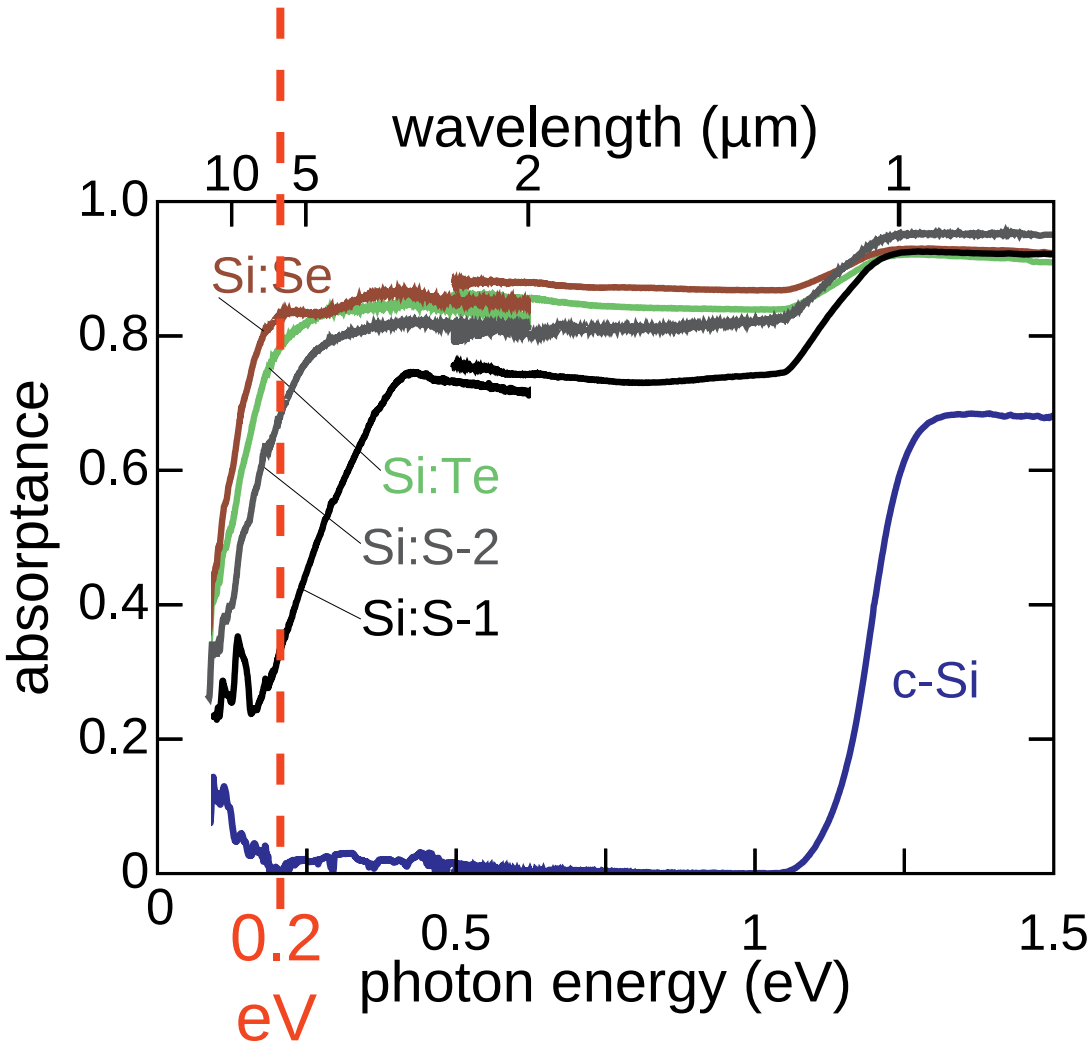








Light–matter interaction



absorption drop-off

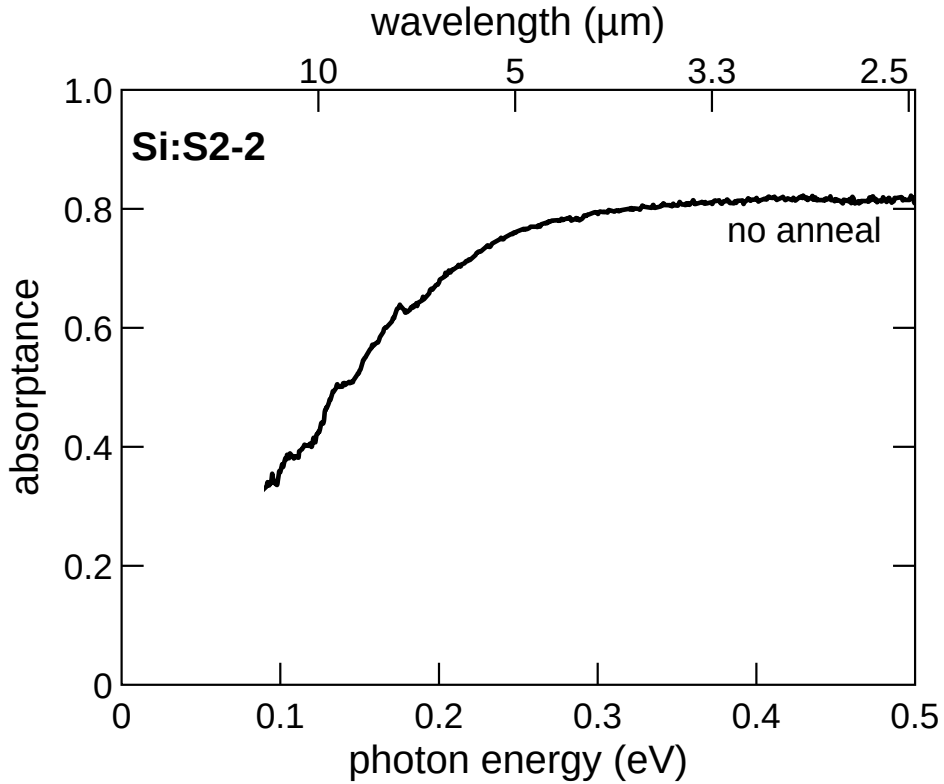
- related to surface morphology
- $\Delta E < 0.2$ eV

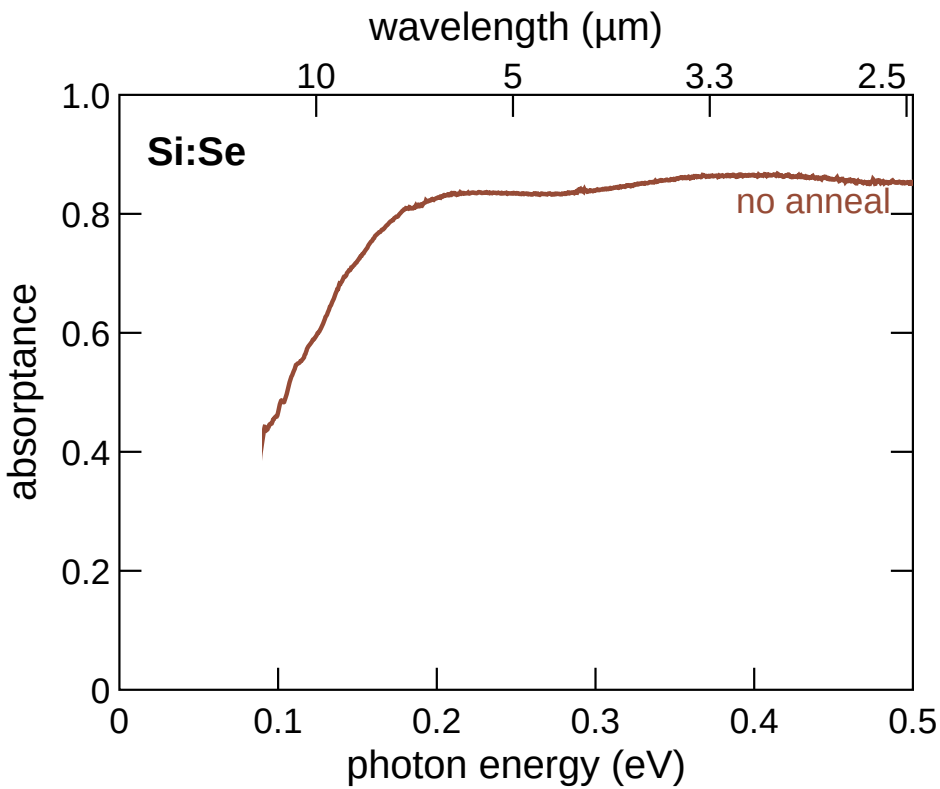
Outline

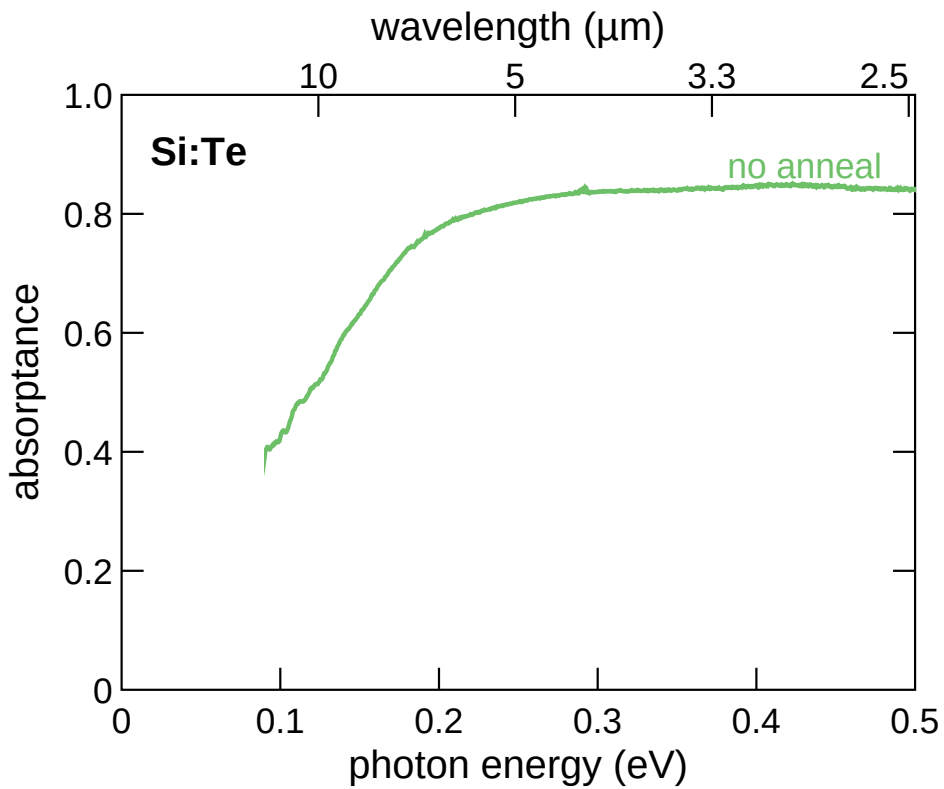
- Mid-IR absorption
- light–matter interaction
- annealing and free carrier absorption

Annealing

before annealing

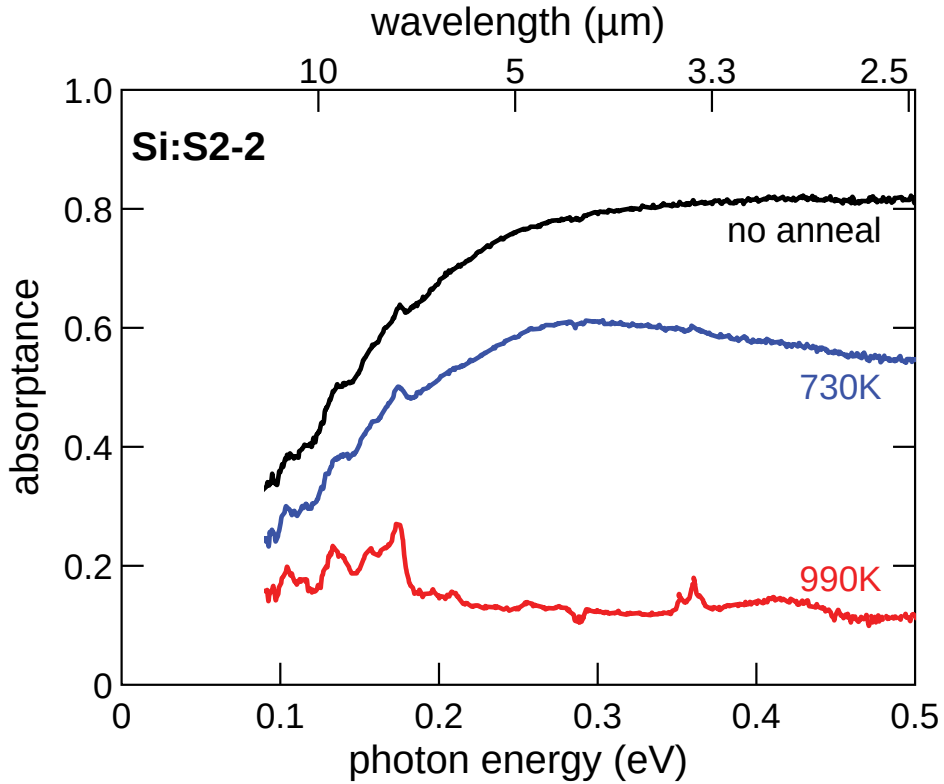


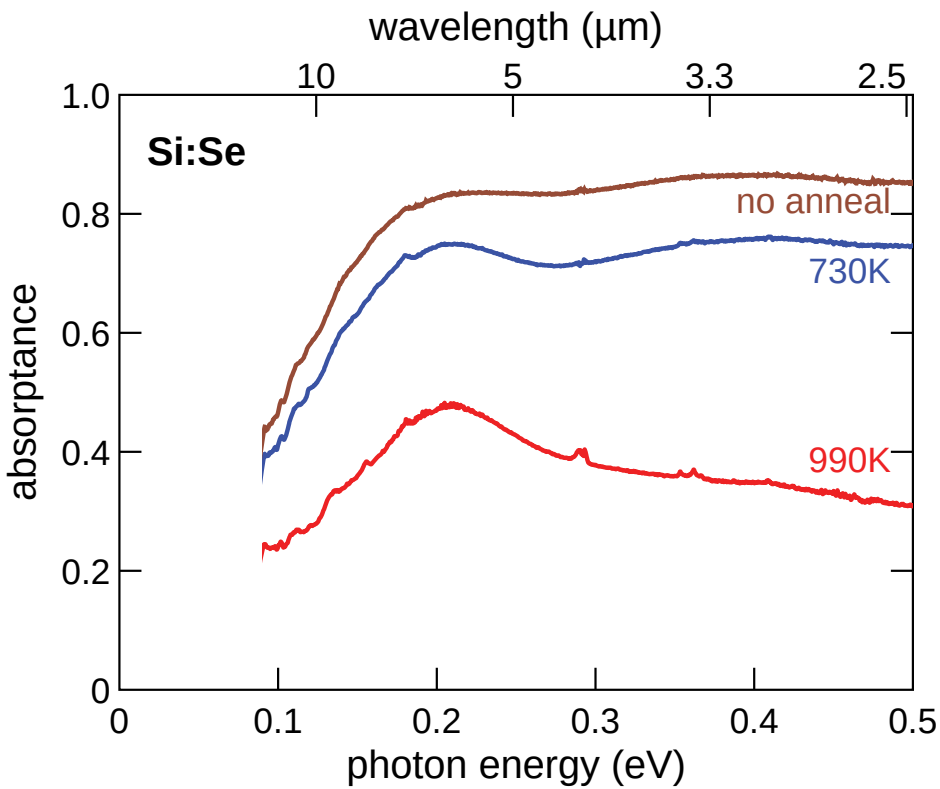


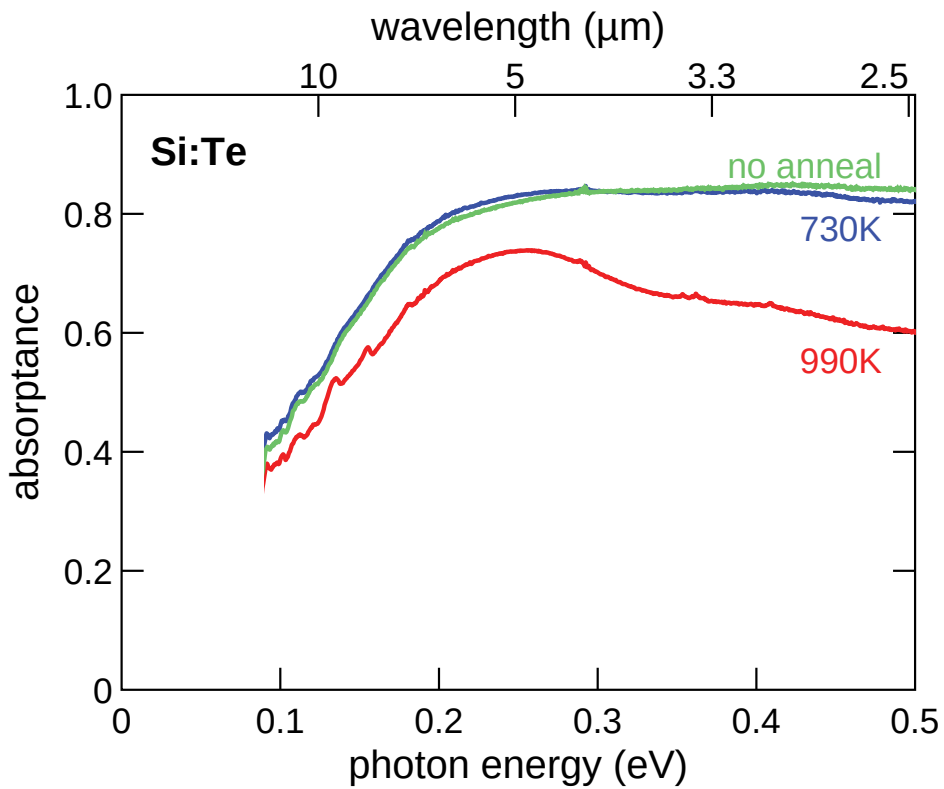


Annealing

abs. decreases after annealing

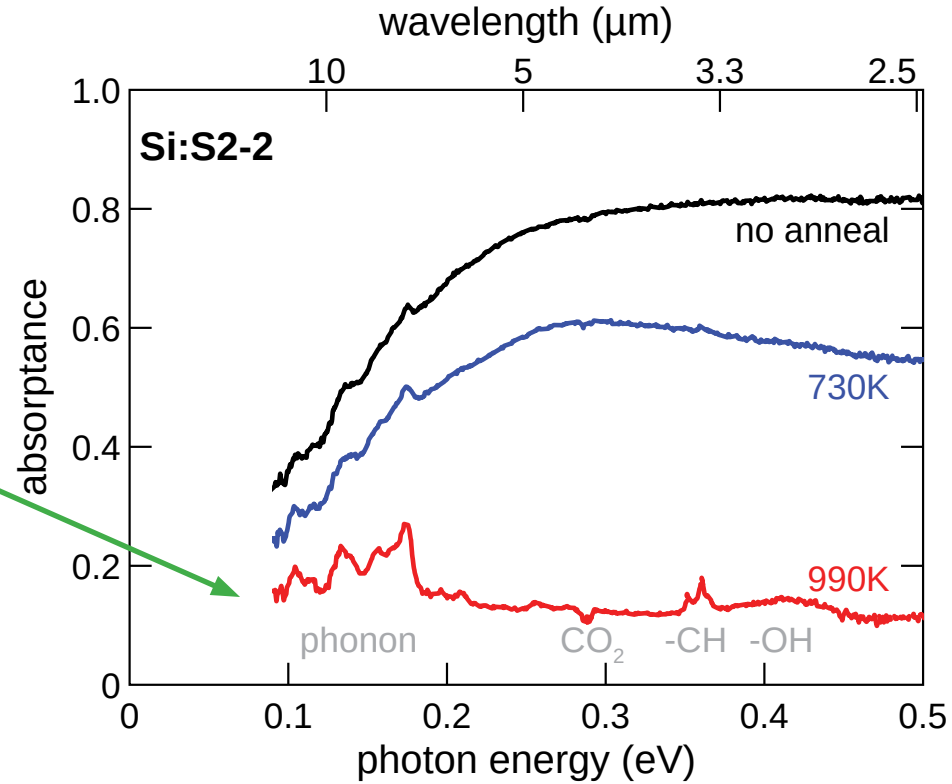


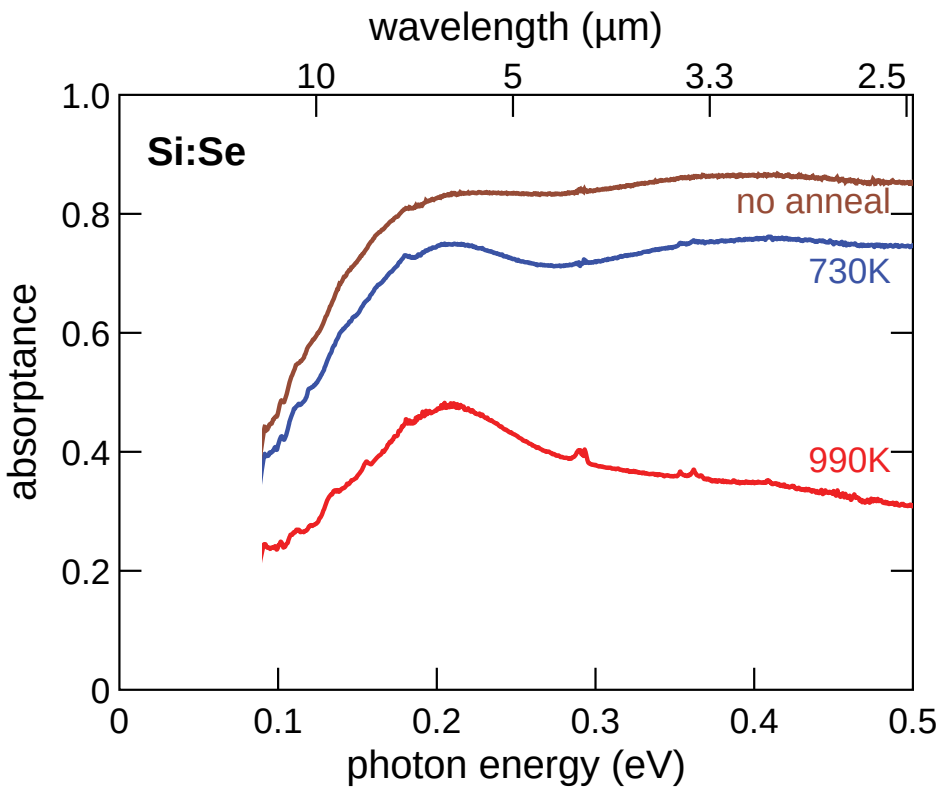


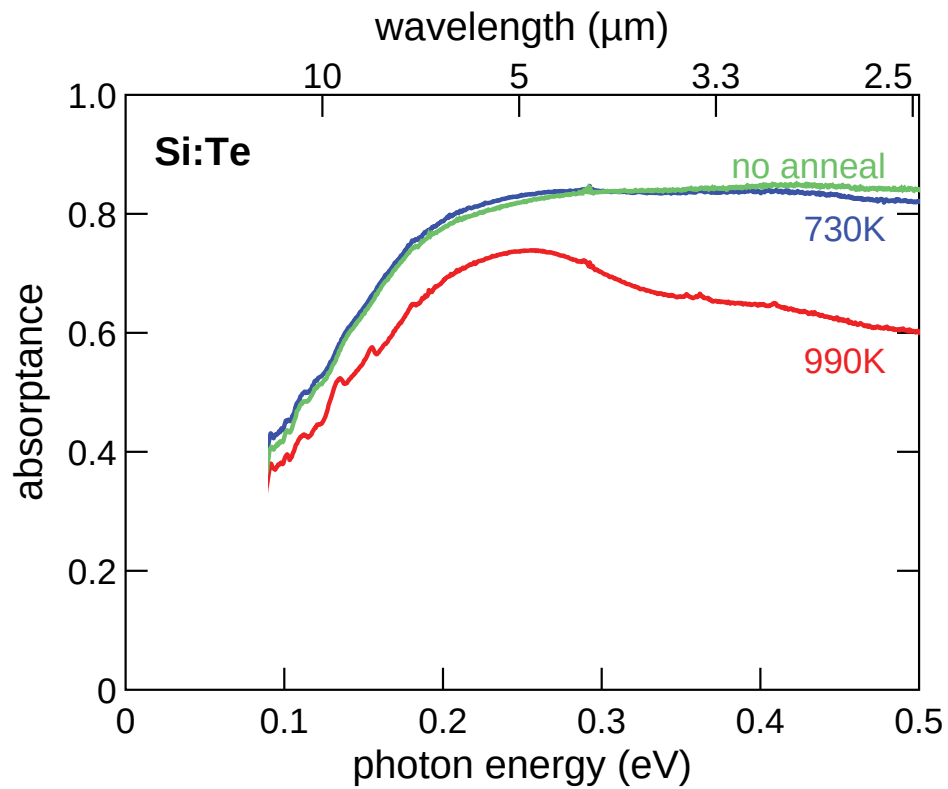


Annealing

known vibration modes

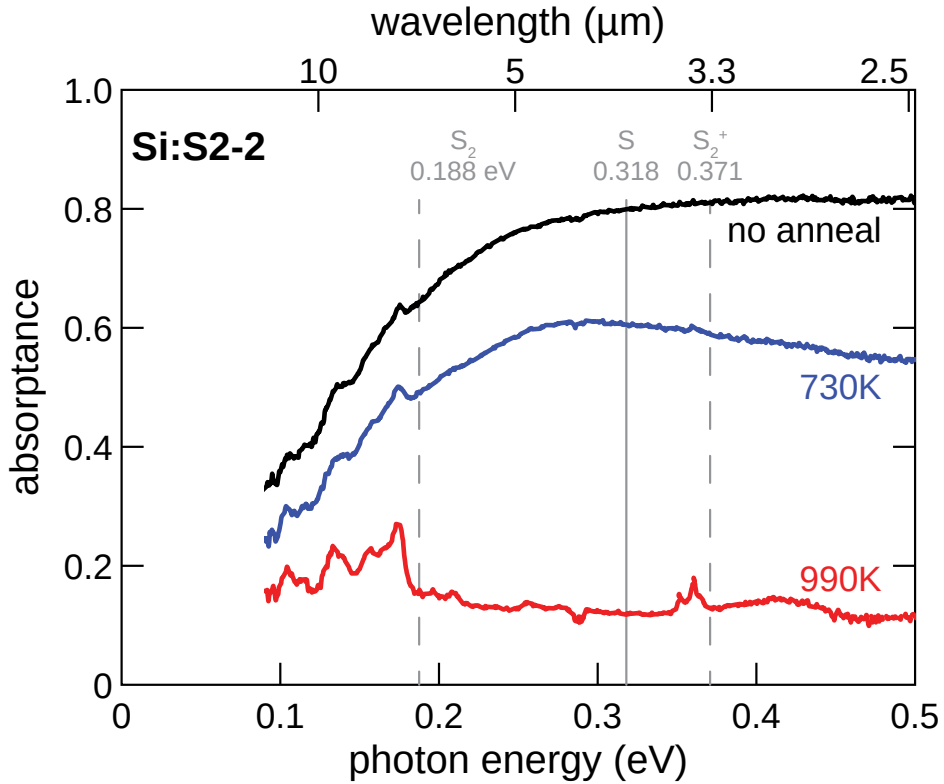


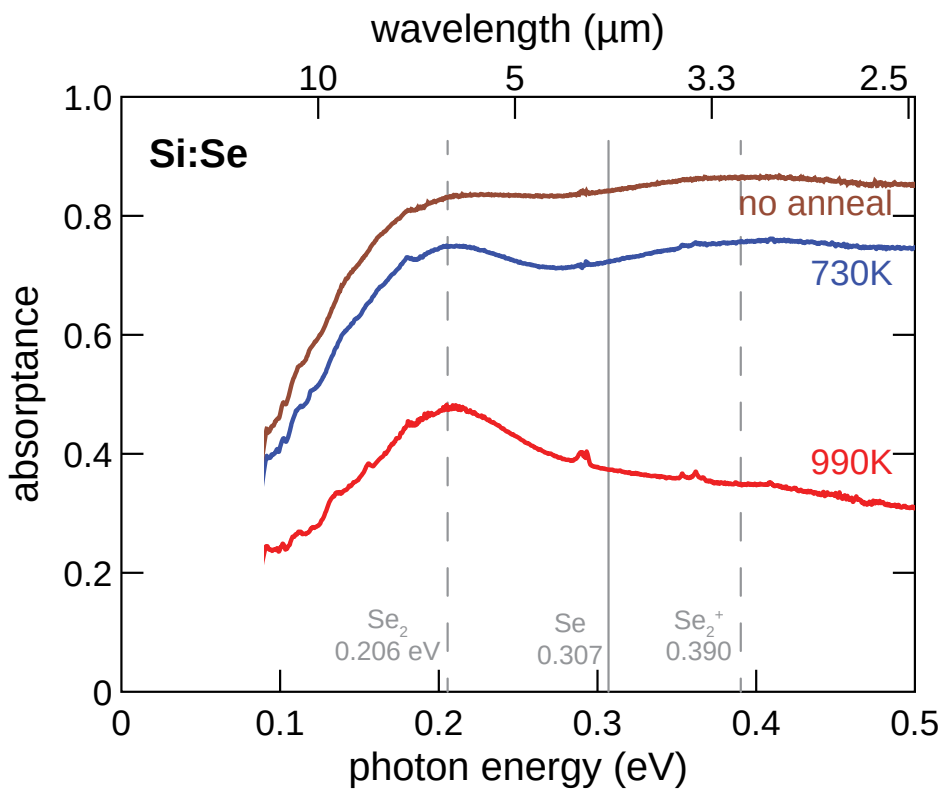


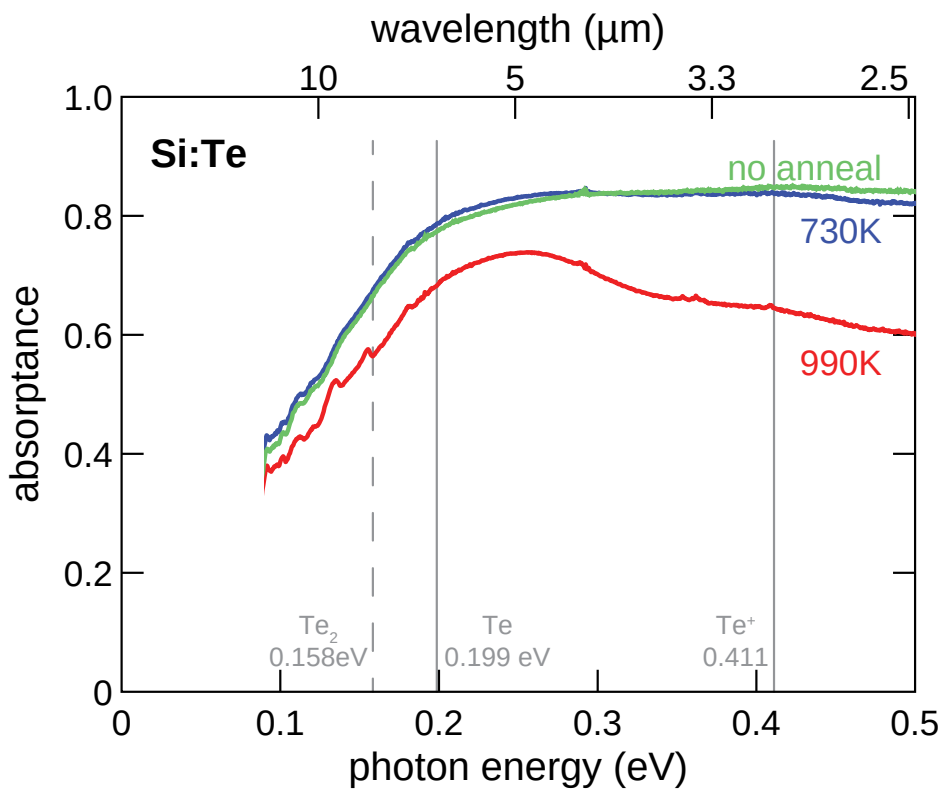


Annealing

no point defect abs. observed

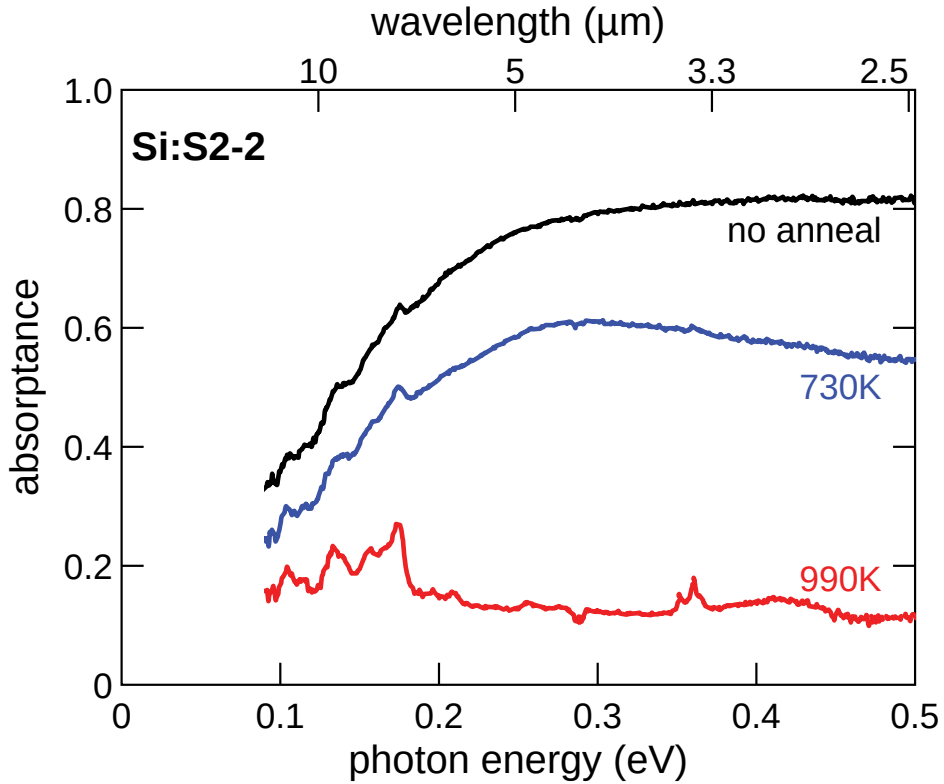


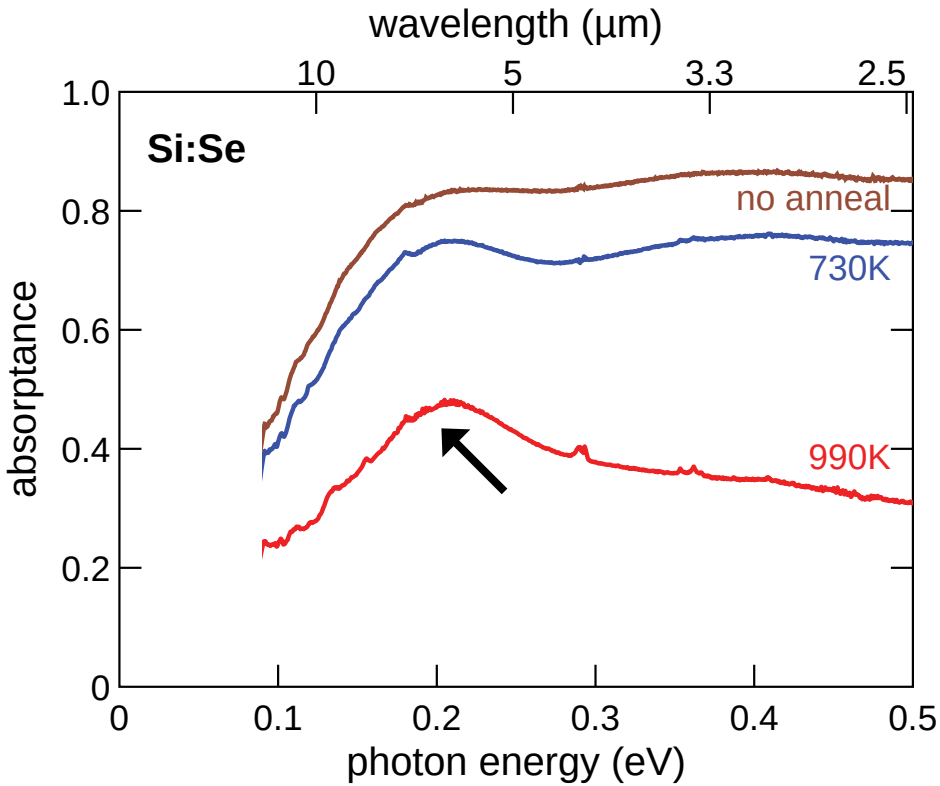


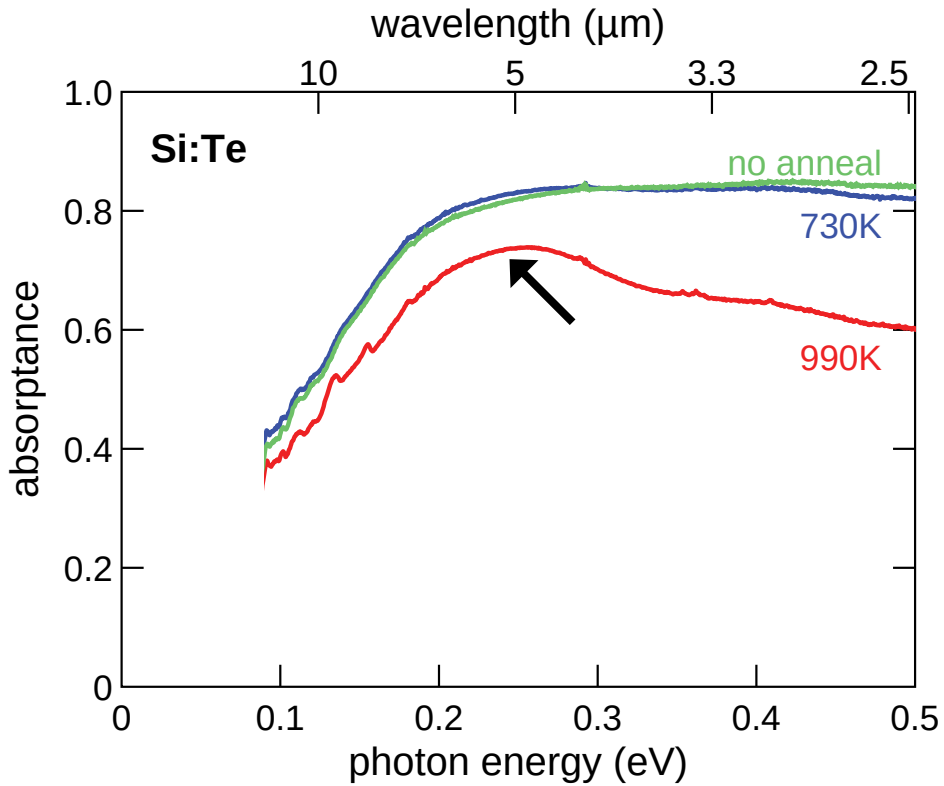


Annealing

broad resonance features







Annealing

free carrier absorption?

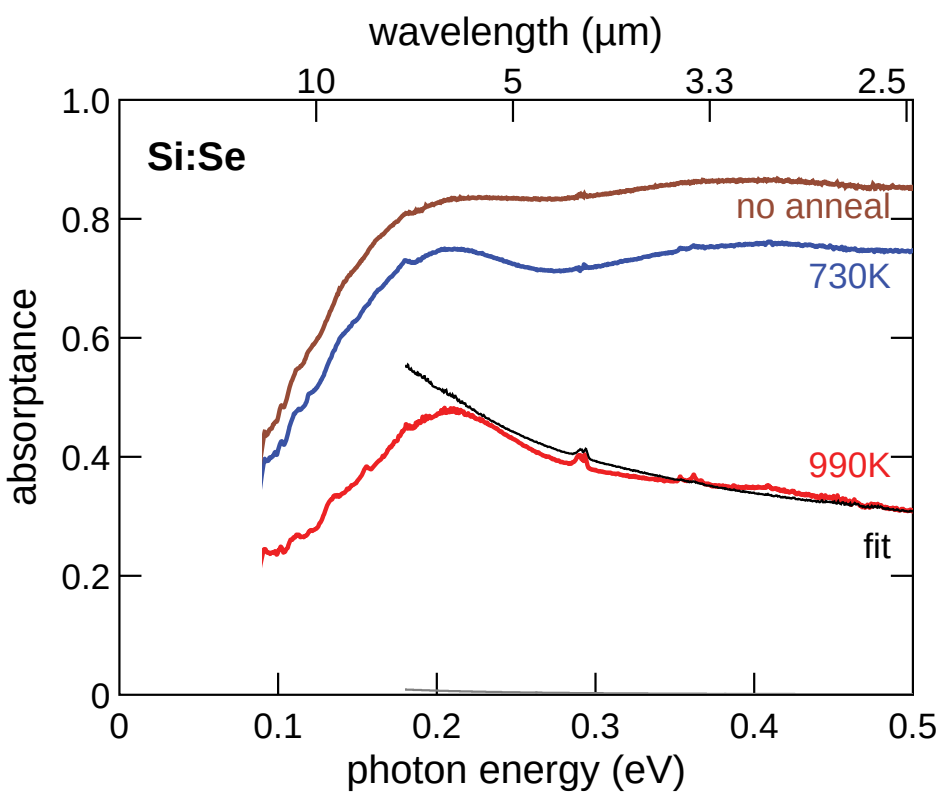
$\alpha_{free} \sim 2 \times 10^{-18} \lambda^2 n$

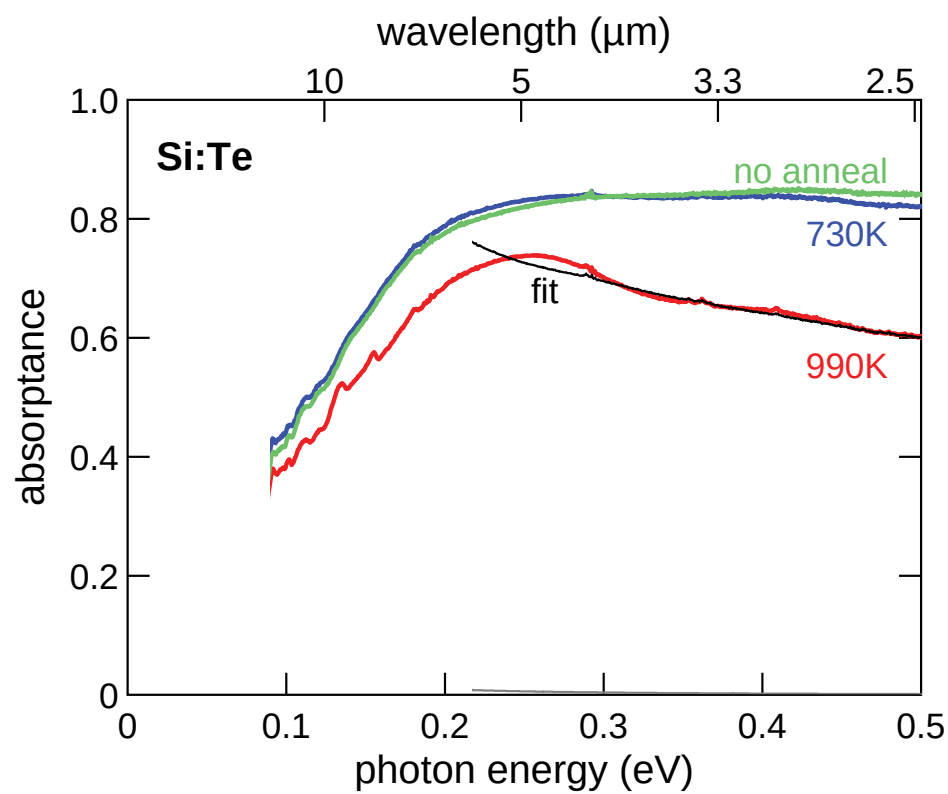
$A = (1-R)[1-exp(-\alpha dm)]$

$A = (1-R)[1-exp(-\alpha_{free} dm - \alpha_{other} dm)]$

$A(\varepsilon) = [1-R(\varepsilon)][1-y\ exp(-x/\varepsilon^2)]$

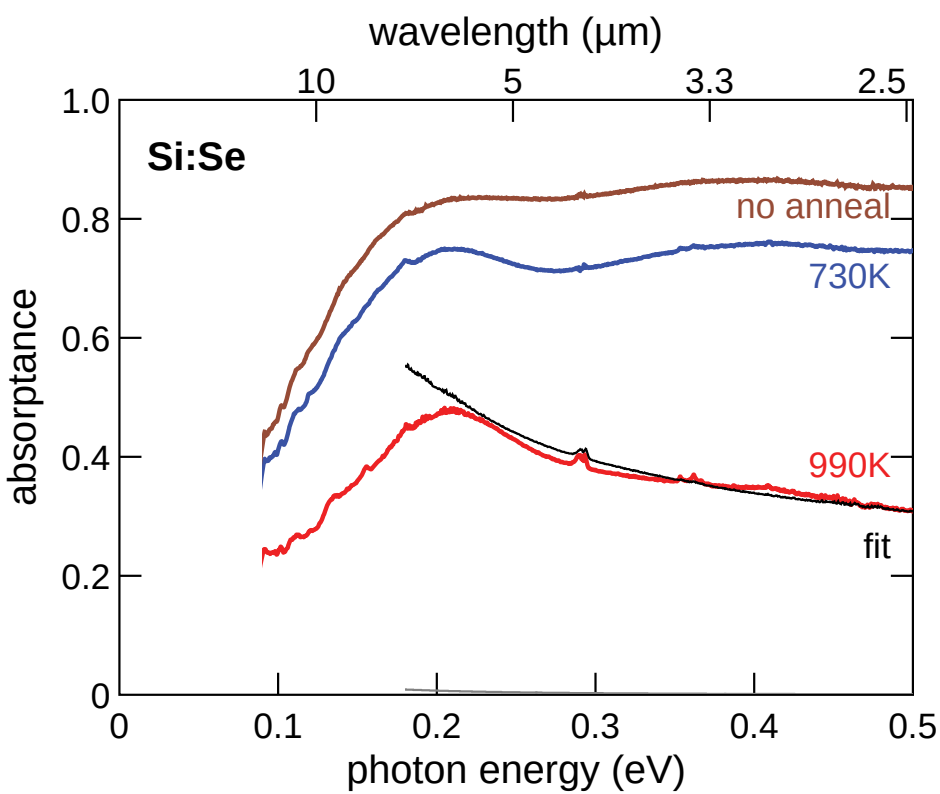
$x = 3 \times 10^{-18} n_{sheet} m$

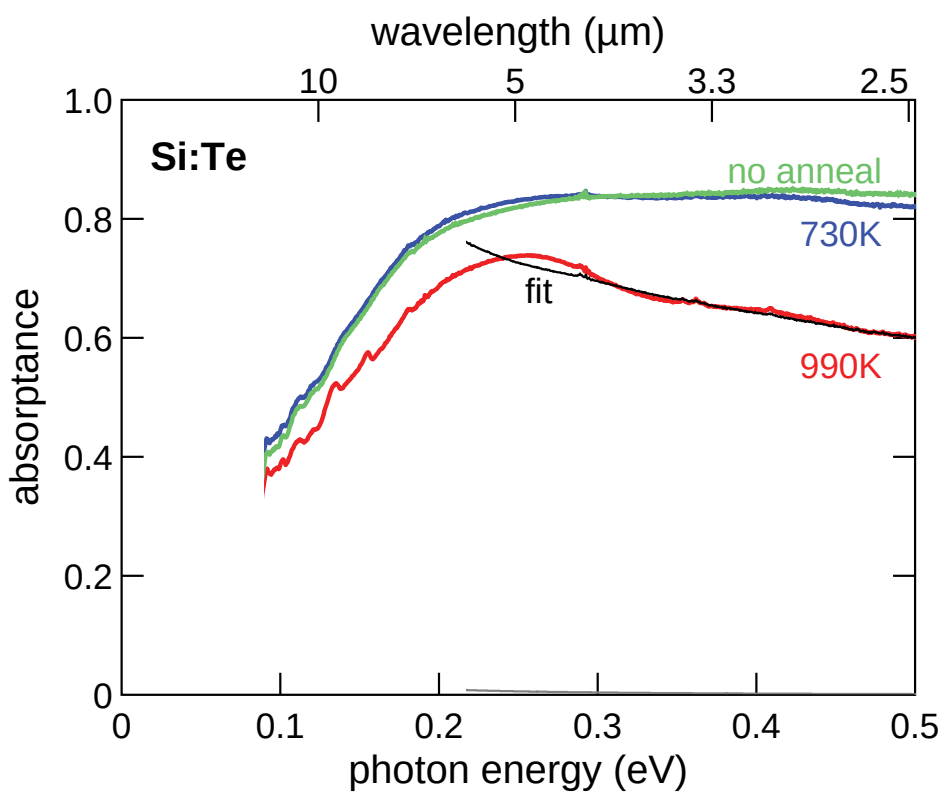




Annealing

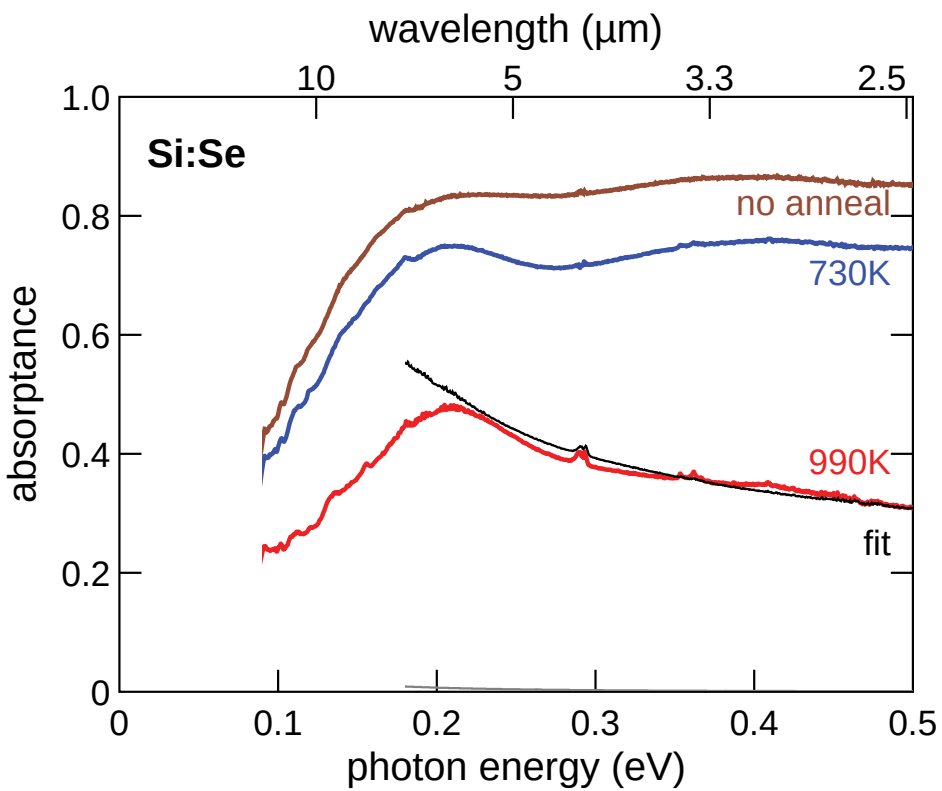
fitting abs. measurements	Hall measurements
$n_{sheet} \times m = 1 \times 10^{16}$ cm^{-2}	$n_{sheet} = 6 \times 10^{12}$ cm^{-2}
$m = 1$; $n_{sheet} = 1 \times 10^{16}$	
$m = 50$; $n_{sheet} = 3 \times 10^{14}$	

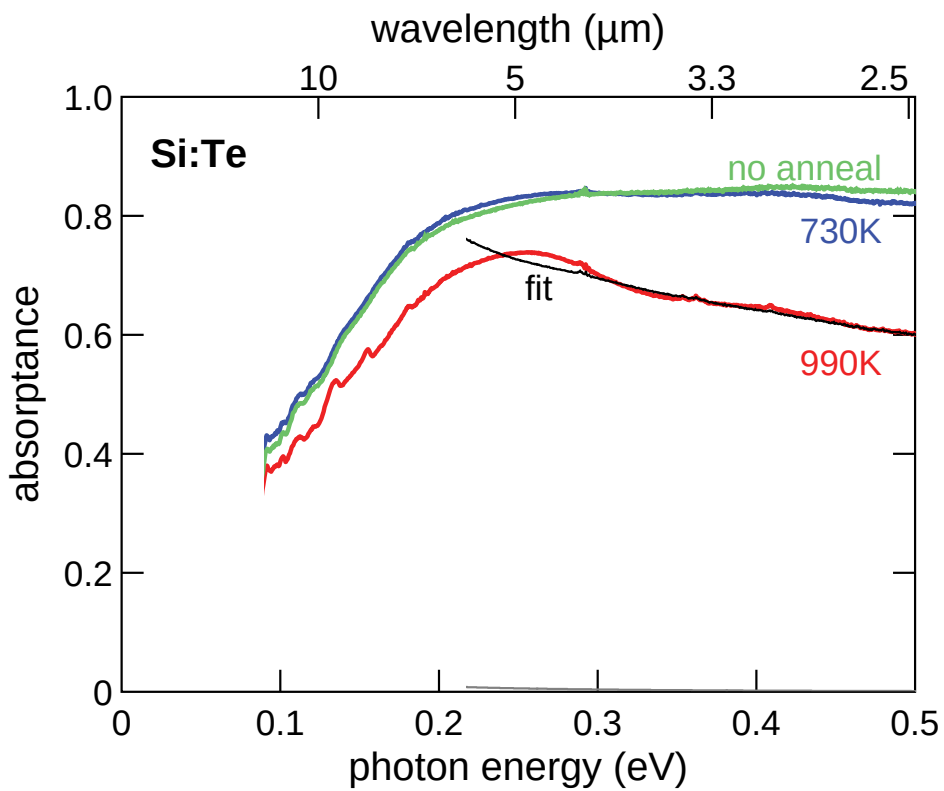




Annealing

- no absorption lines from known point defects
- resonance features likely from multiple effects
- observe λ^2 dependence but cannot confirm if its from free carrier absorption





Summary

- Mid-IR absorption
  → absorption drop-off
  → after annealing resonance features

- absorption drop-off
  → related to surface morphology
  → $\Delta E < 0.2$ eV

- resonance feature
  → likely from multiple effects
  → λ^2 dependence

Thanks!