# Below-band gap absorption in microstructured silicon

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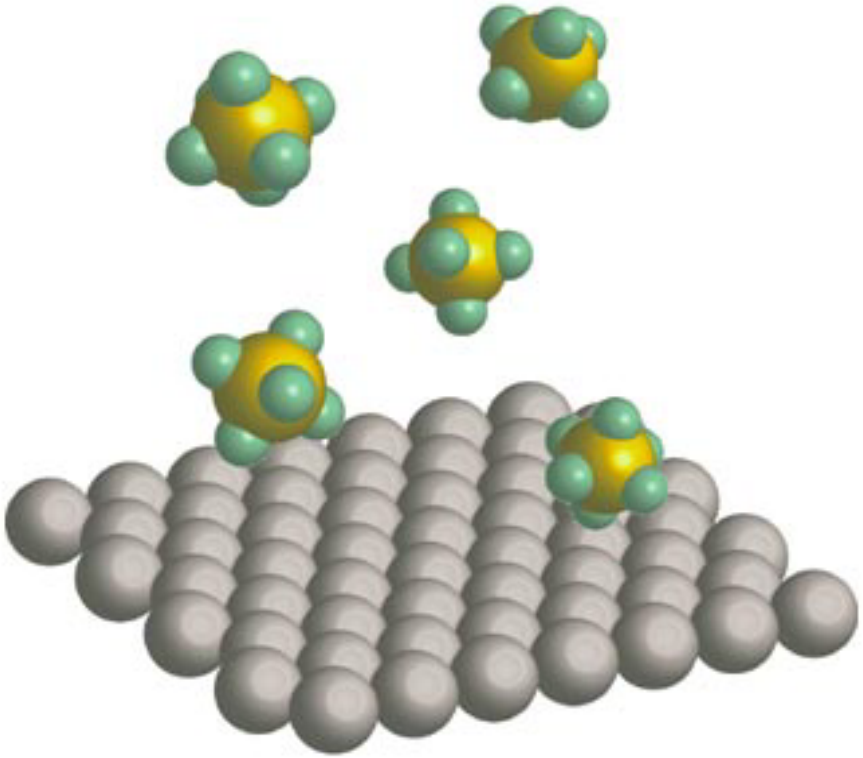
**Harvard University**

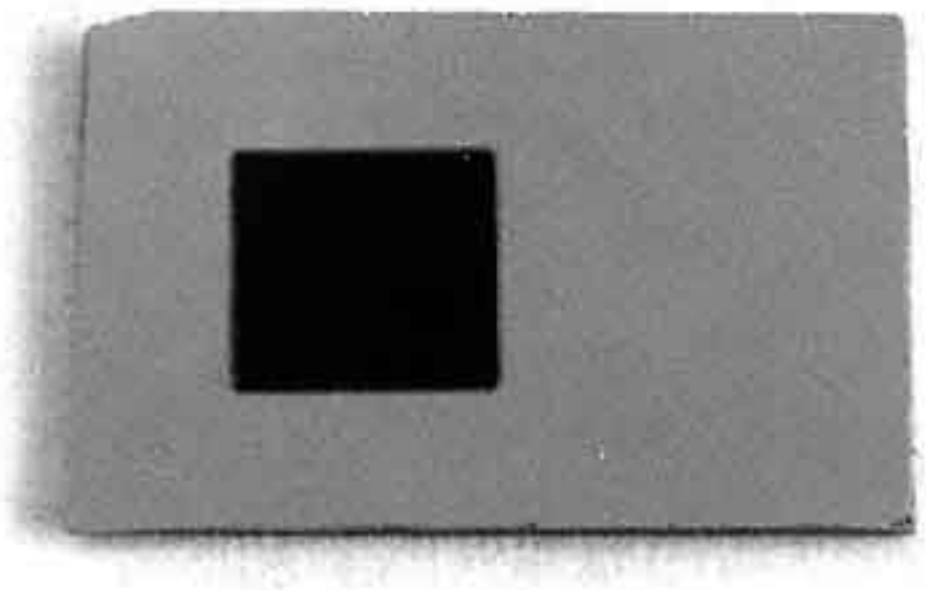
# Microstructuring Silicon



irradiate with 100 fs 10 kJ/m$^2$

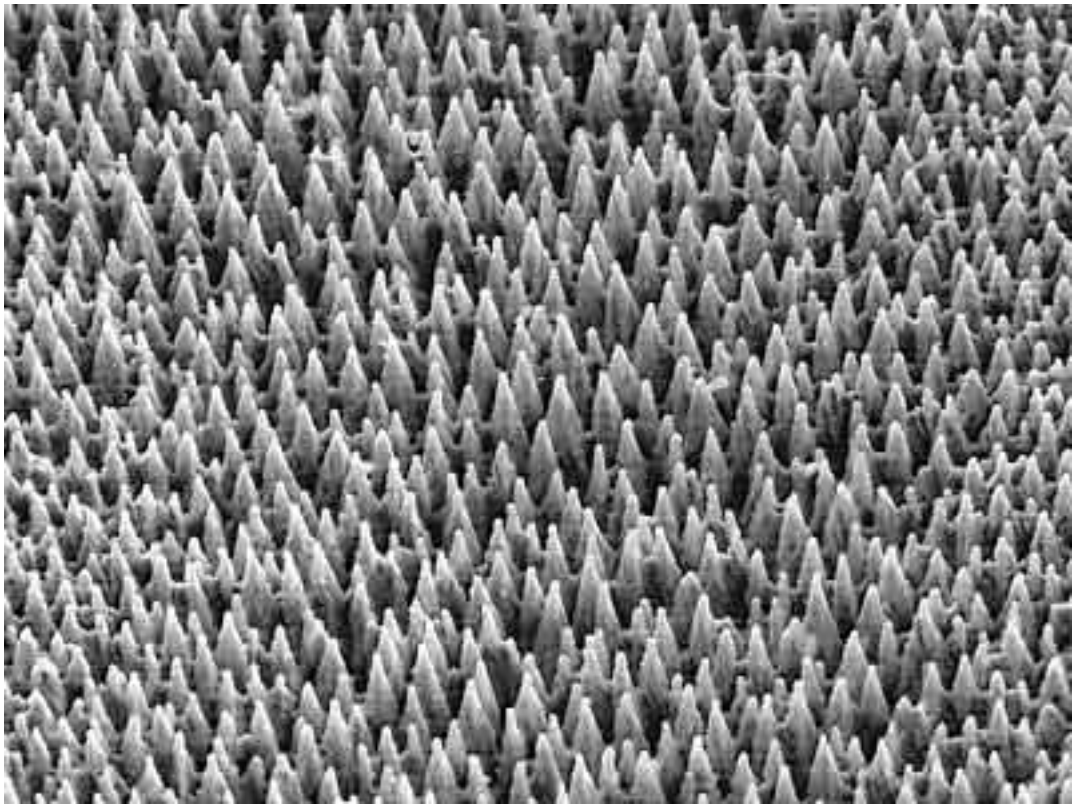
*Her et al. Appl. Phys. Lett.* **73**, *1673 (1998)*

# Black Silicon



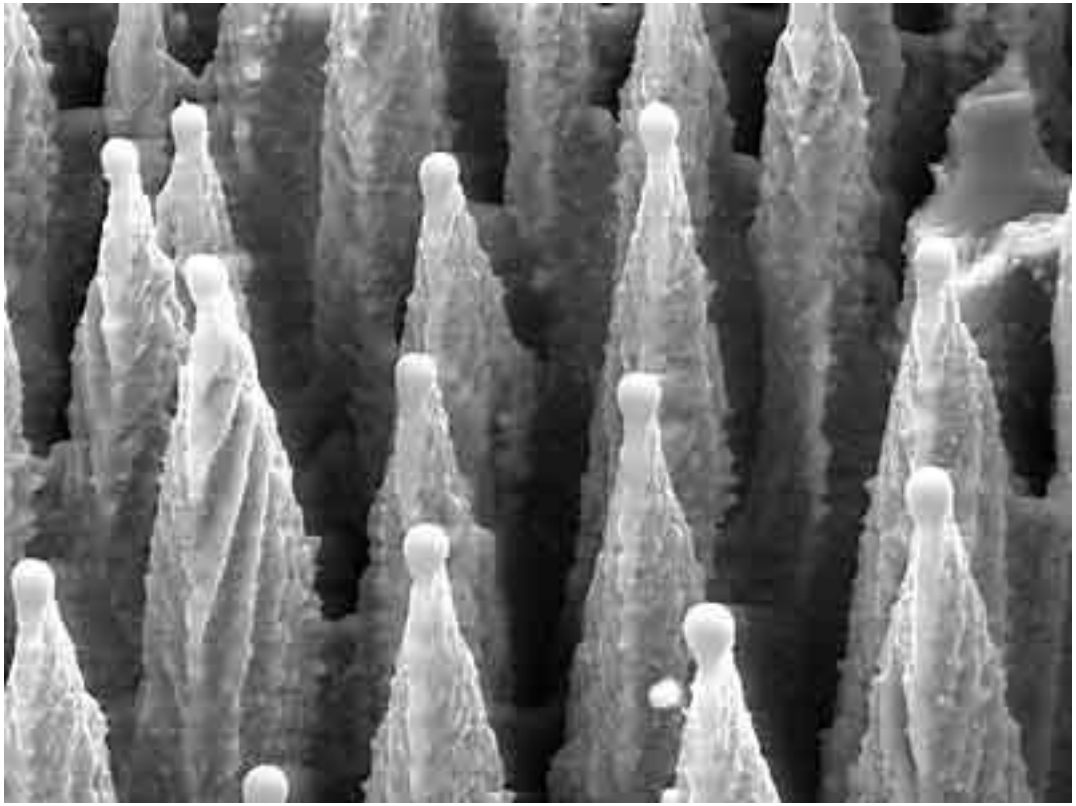
5 mm

# *Microstructuring Silicon*



20 µm

# *Microstructuring Silicon*



4 µm

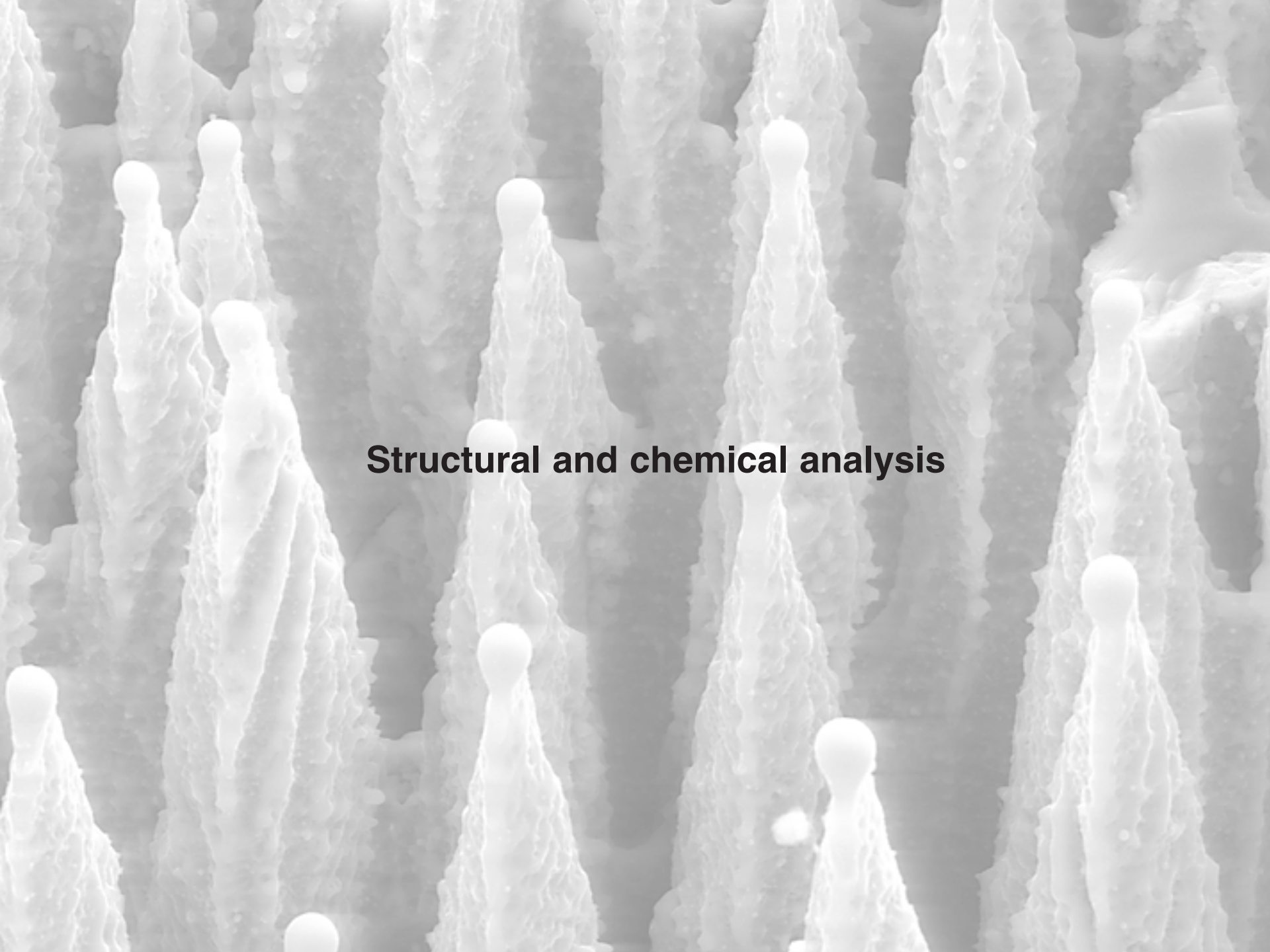
# Outline

I. Characterization of silicon microspikes

II. Optical properties

III. Below-band gap photocurrent

IV. Conclusion



# Structural and chemical analysis

# *Structural properties*

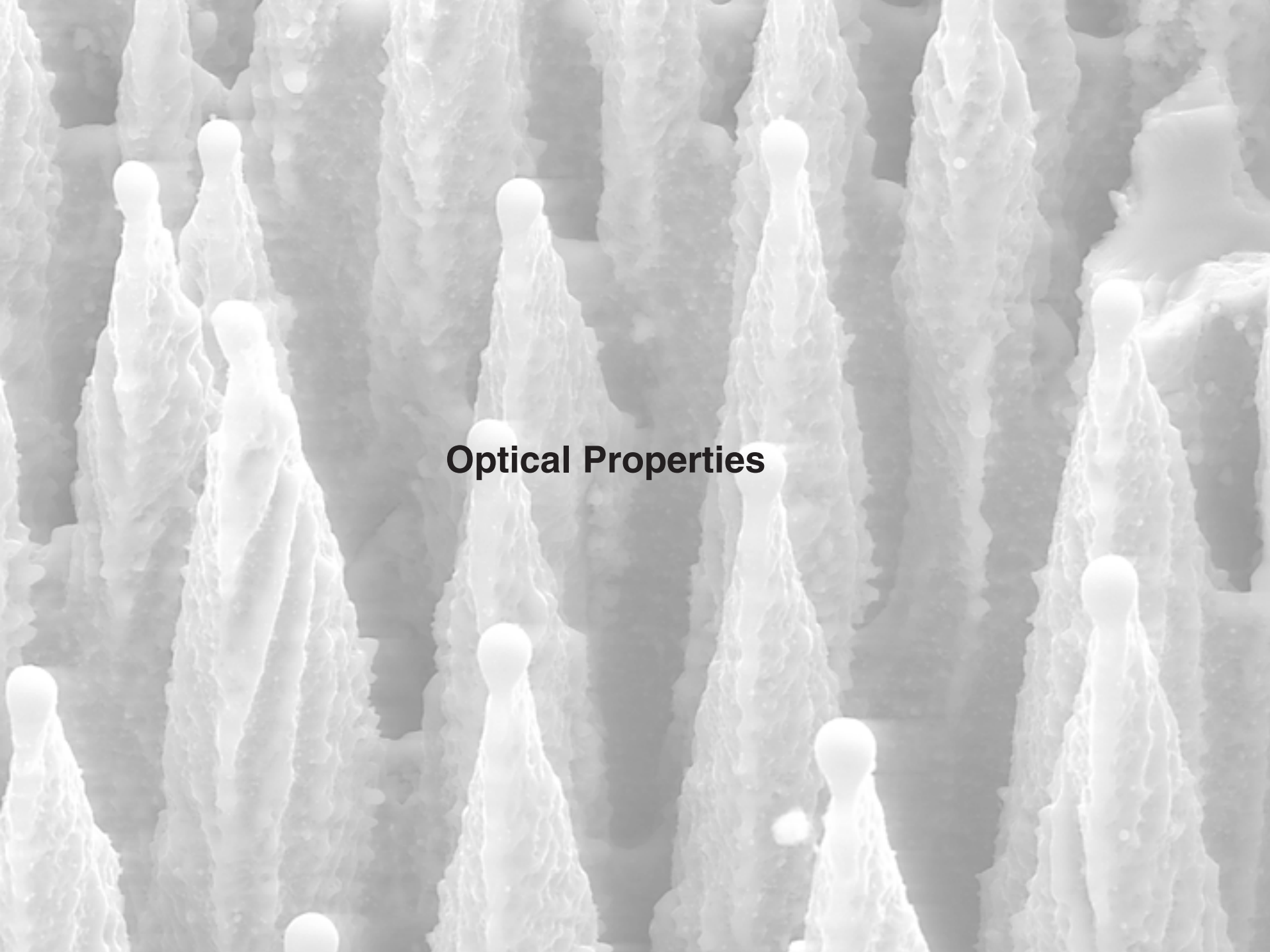
**Ion channeling and electron backscattering**

- Microstructured silicon retains crystalline order
- High density of defects

# *Chemical analysis*

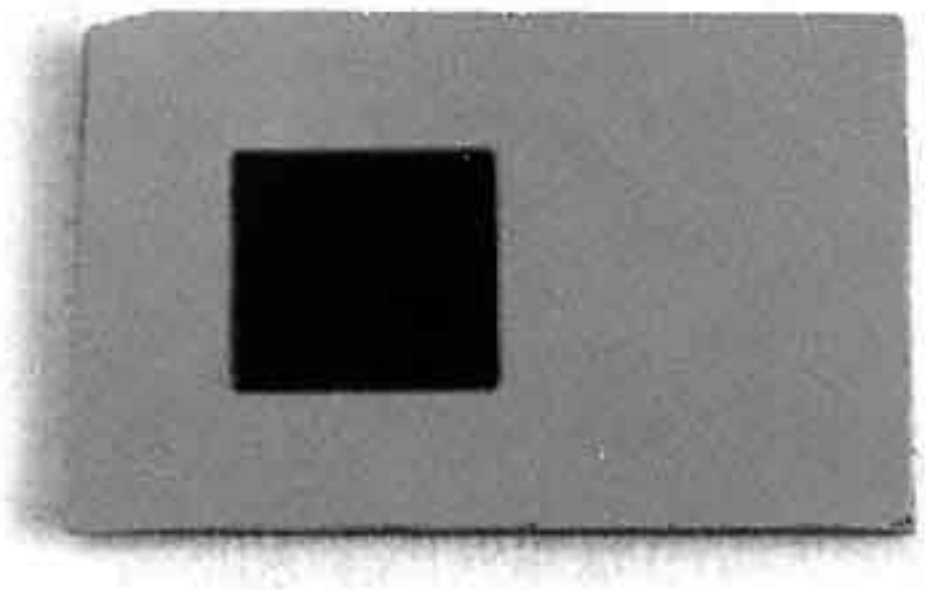
**Secondary Ion Mass Spectrometry (SIMS)**

- High concentration of sulfur (~ $10^{20}$ $cm^{-3}$)
- High concentration of fluorine (~ $10^{17}$ $cm^{-3}$)



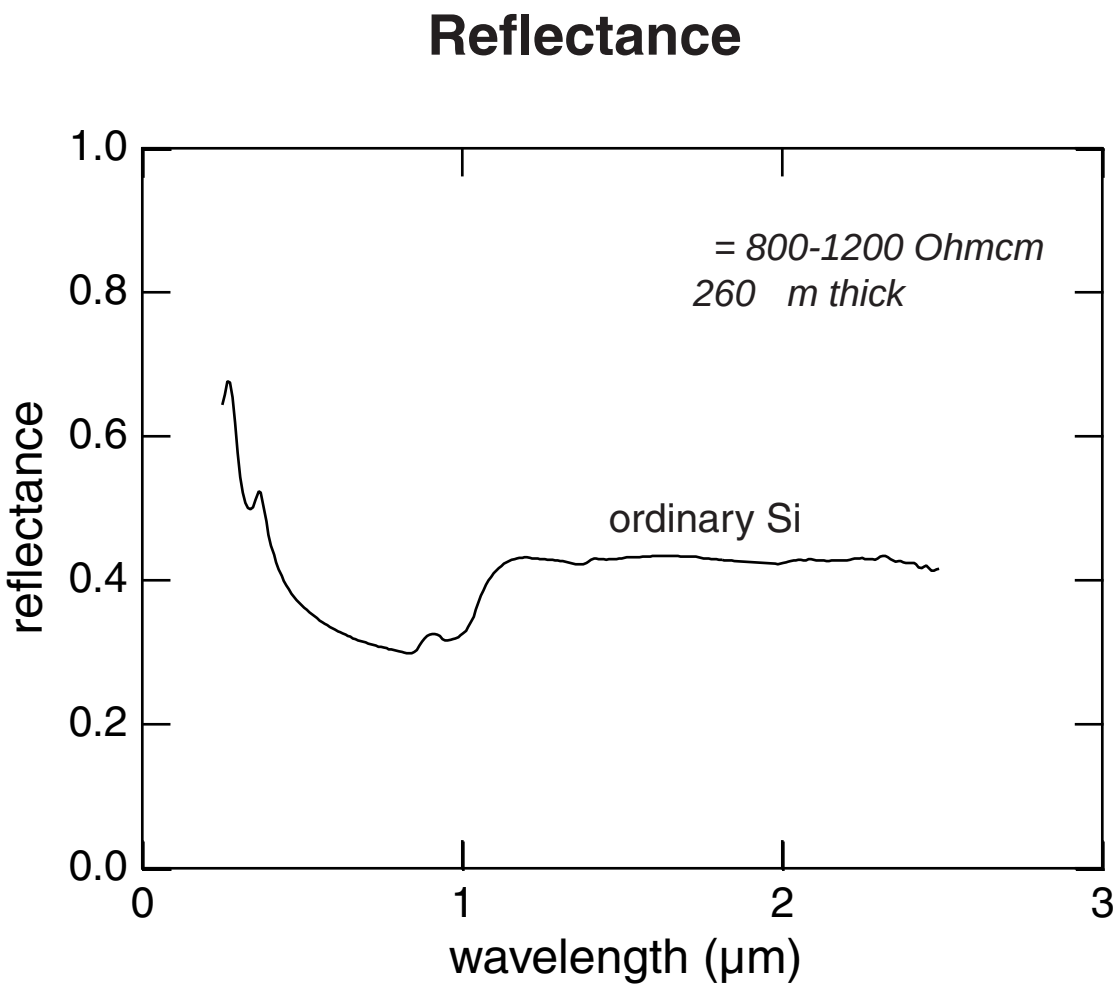
# Optical Properties

# Black Silicon



5 mm

# *Ordinary silicon*



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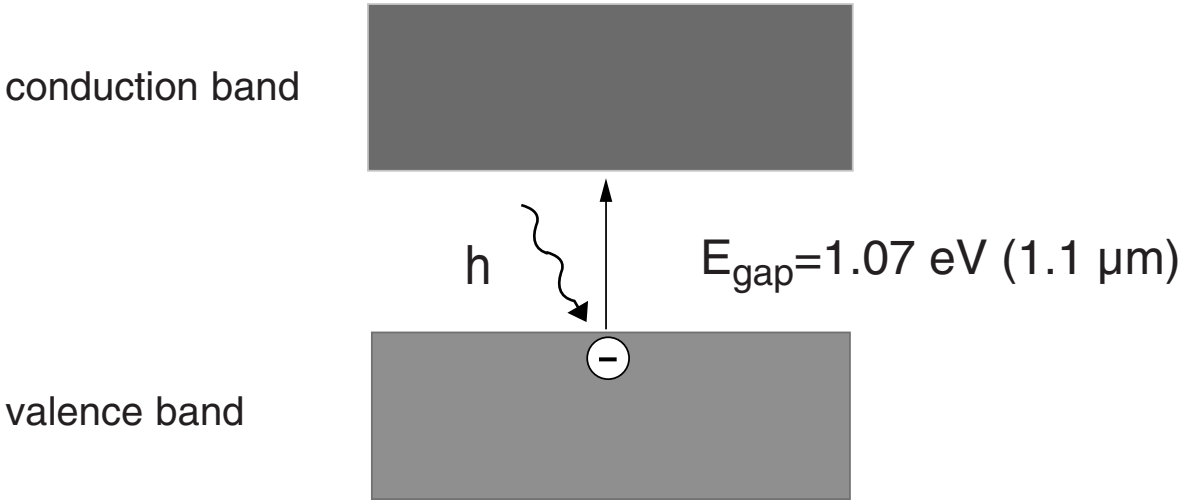
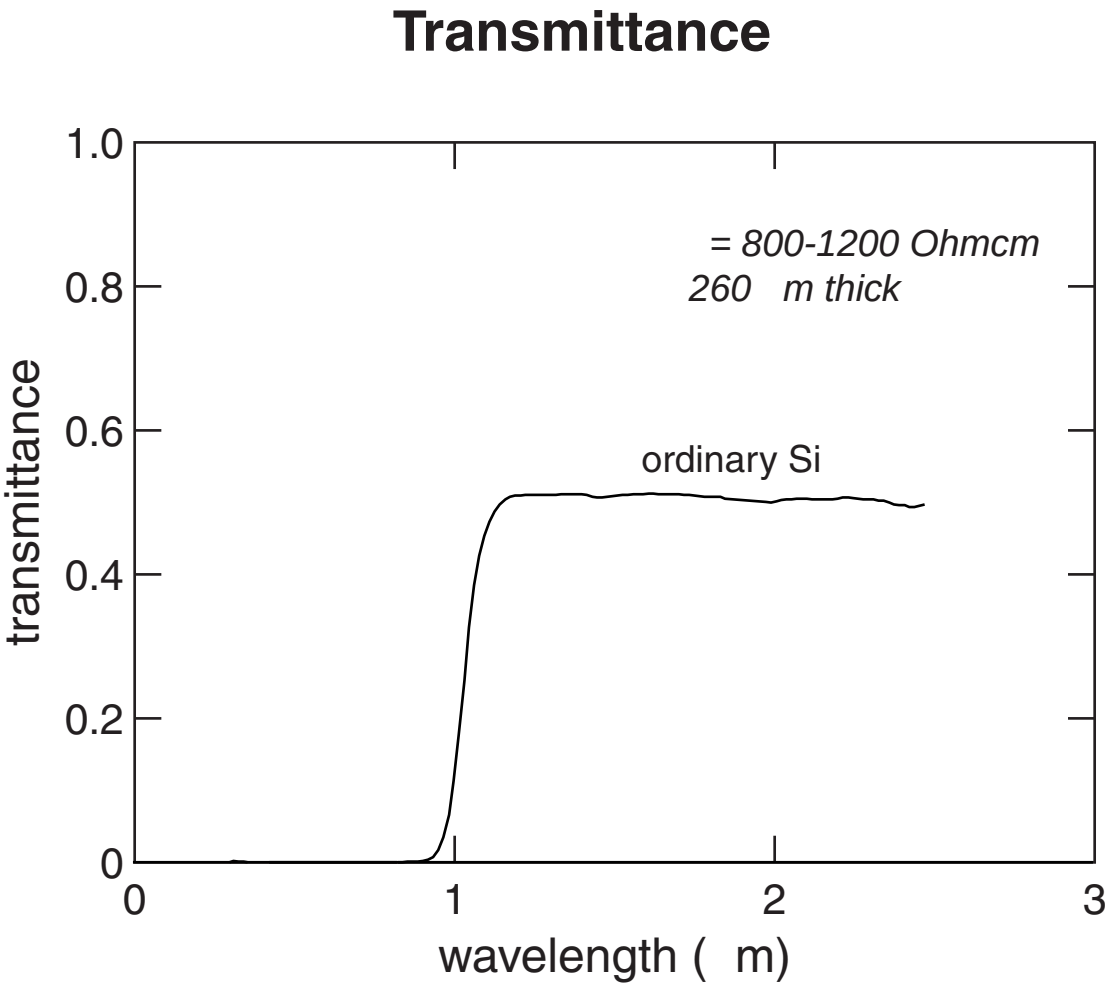



**Only wavelengths < 1.1 μm are absorbed**

# Ordinary silicon



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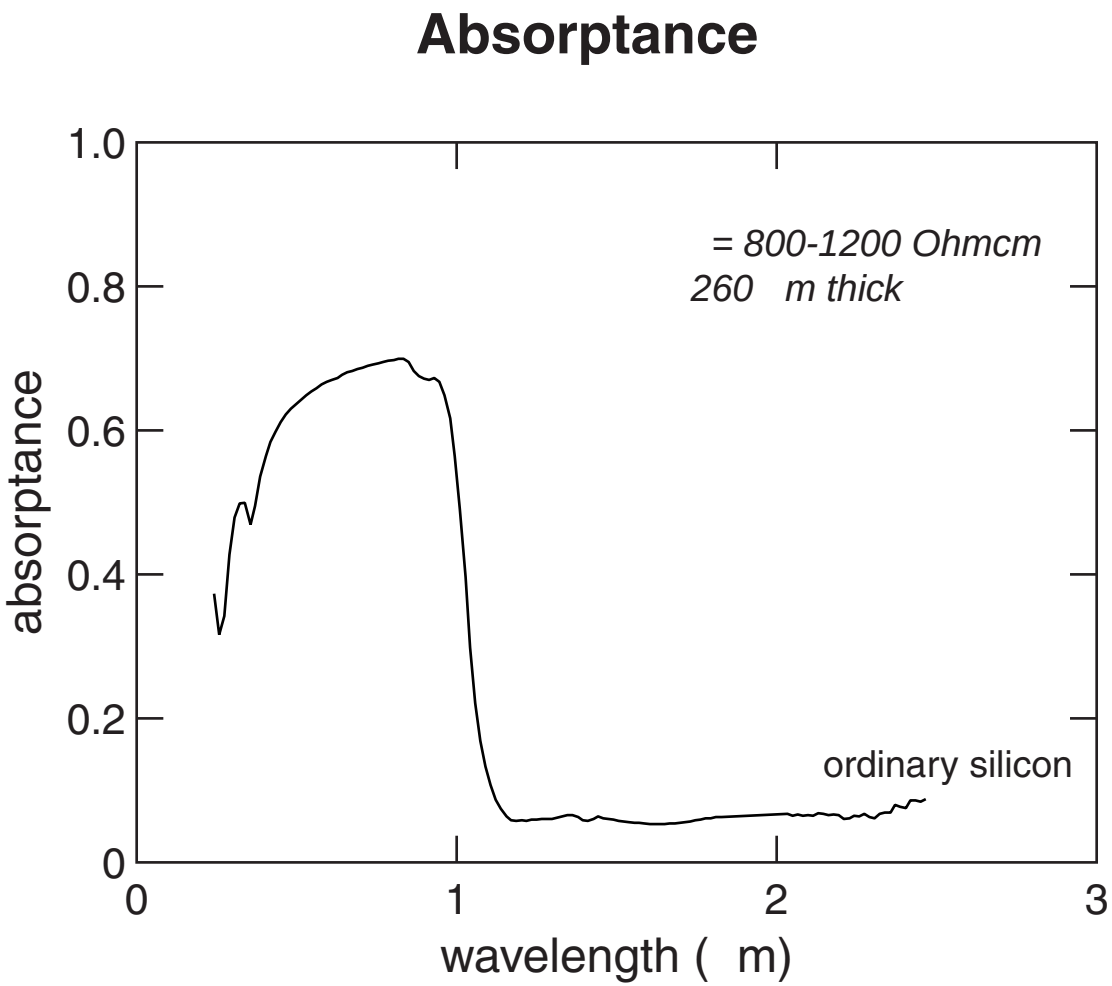
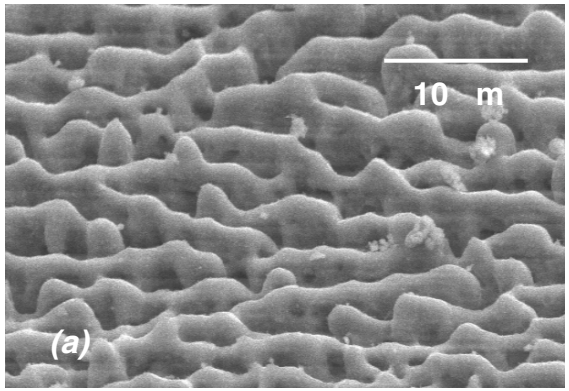
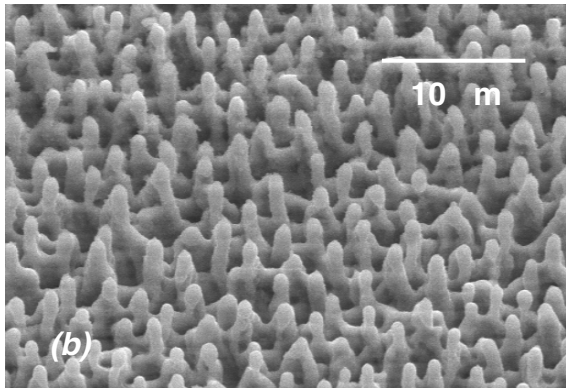


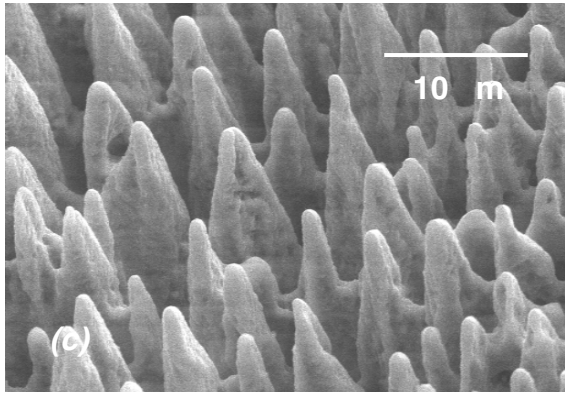
# *Microstructured silicon*



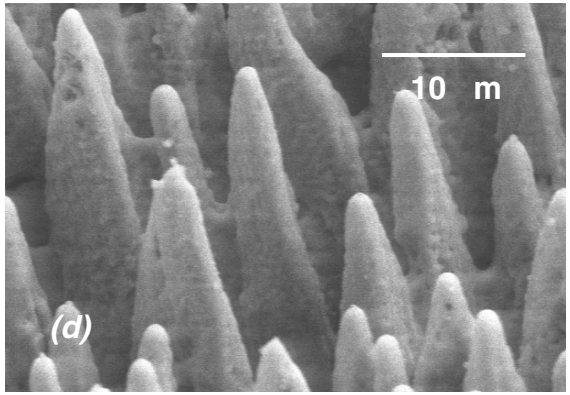

1-2 µm




4-7 µm



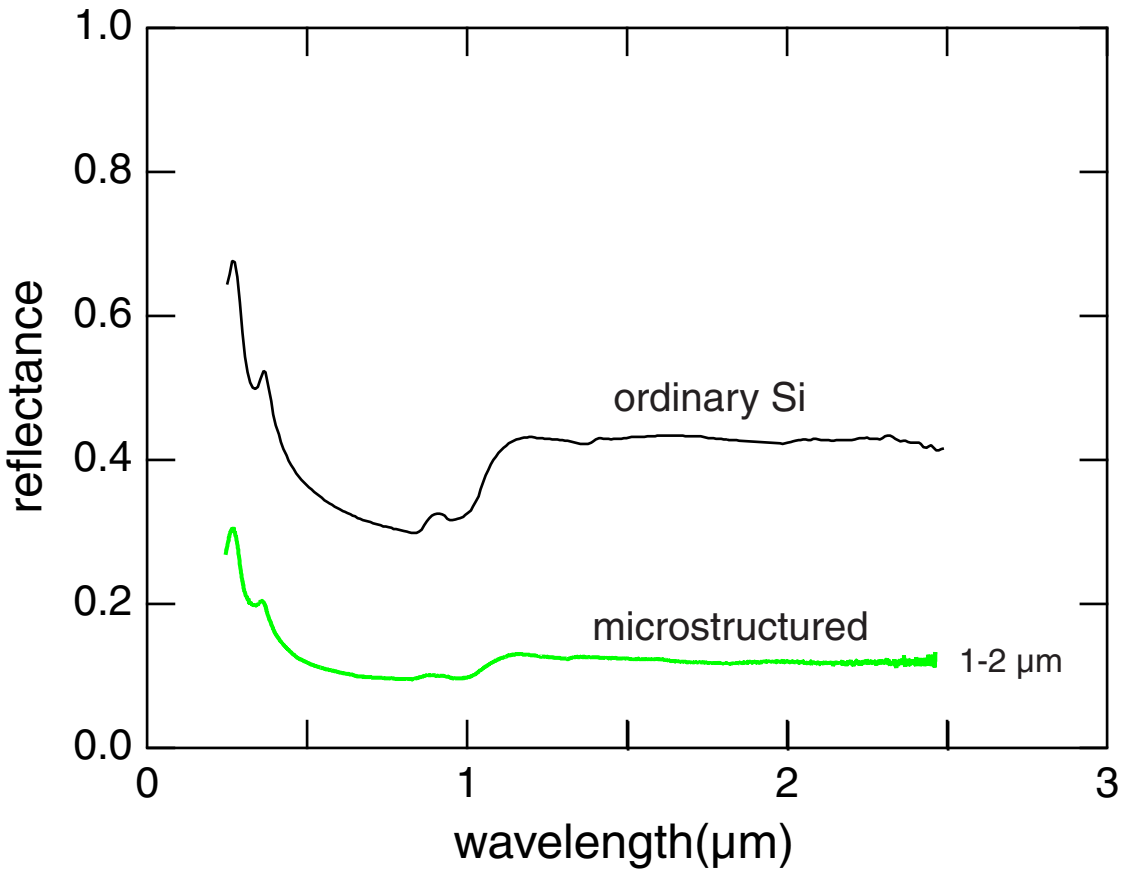

10-12 µm




18-20 µm

# *Microstructured silicon*

## Total integrated reflectance



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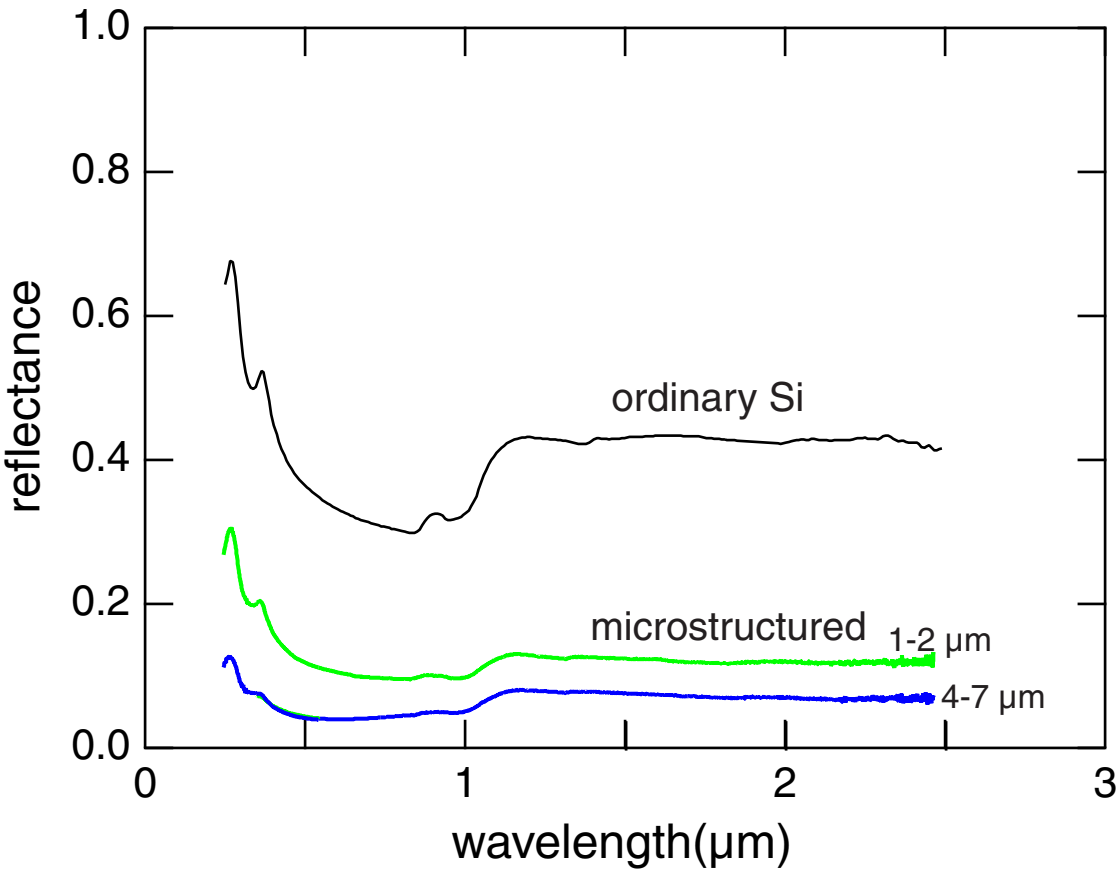
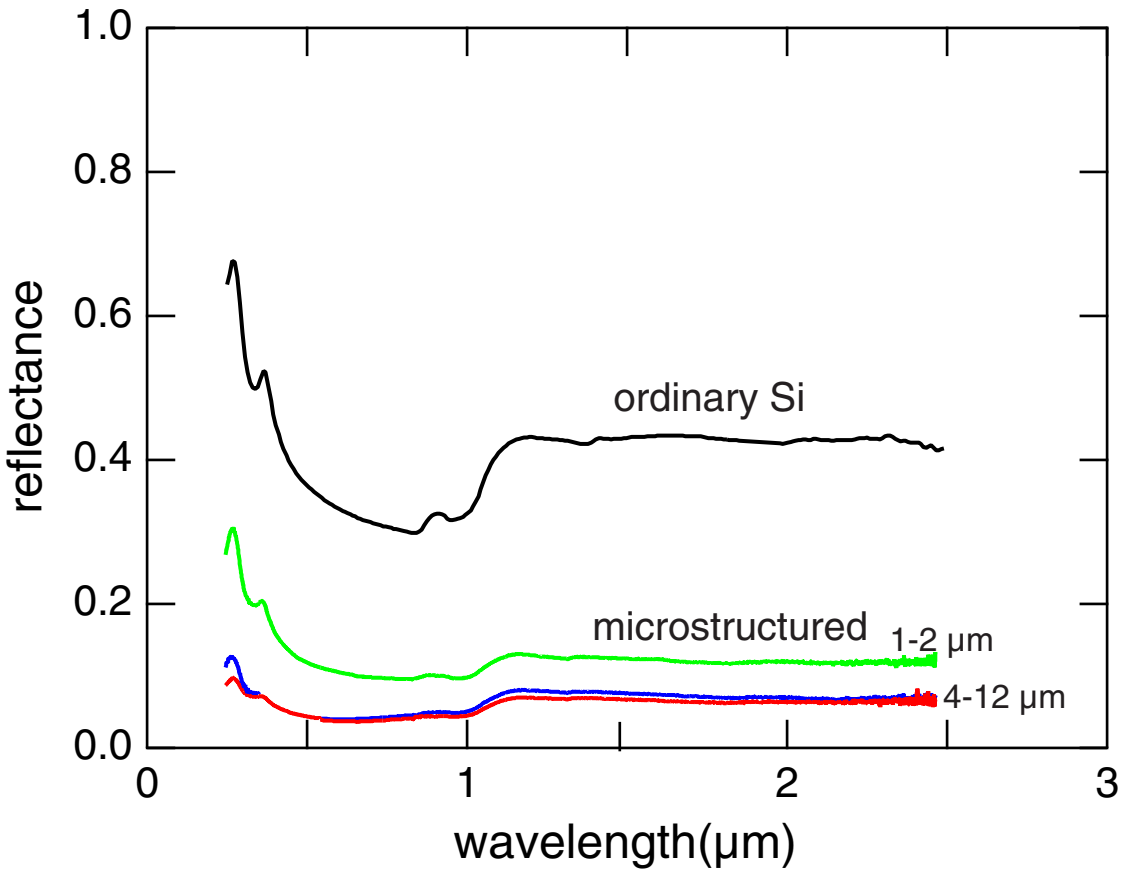


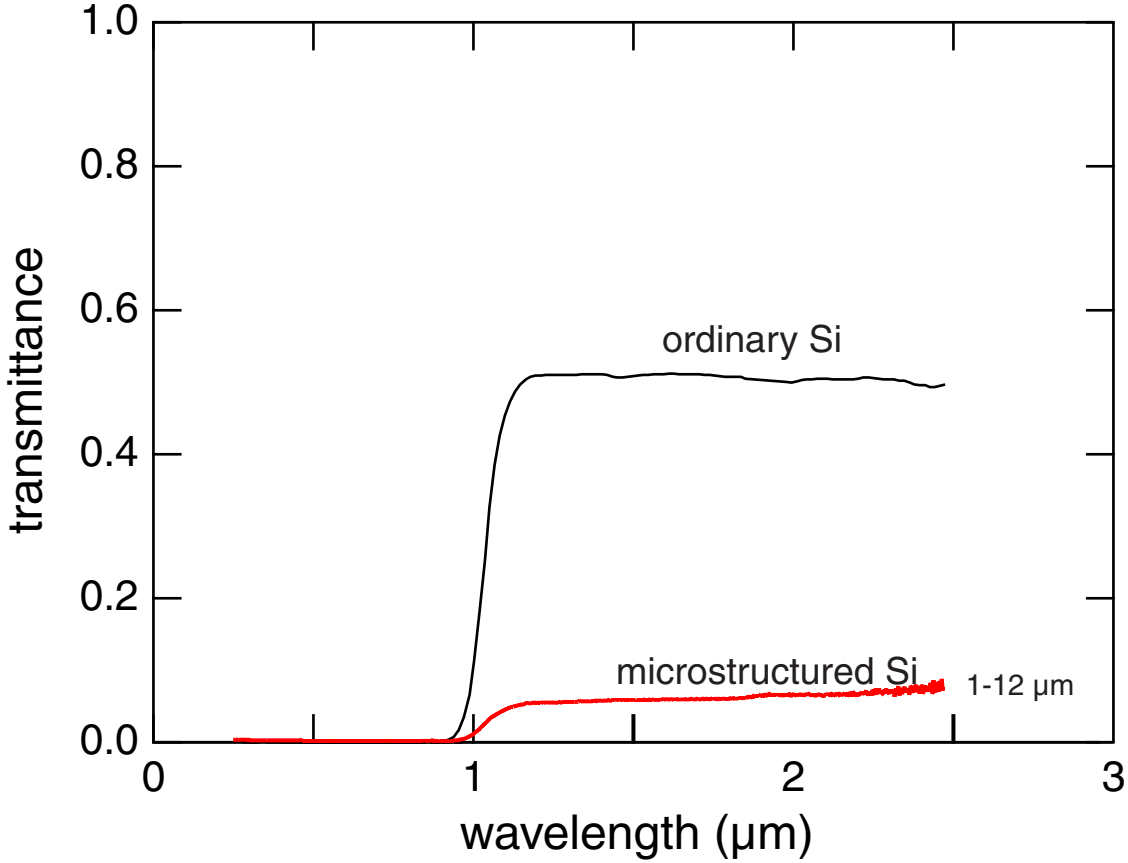
# *Microstructured silicon*

## Total integrated reflectance

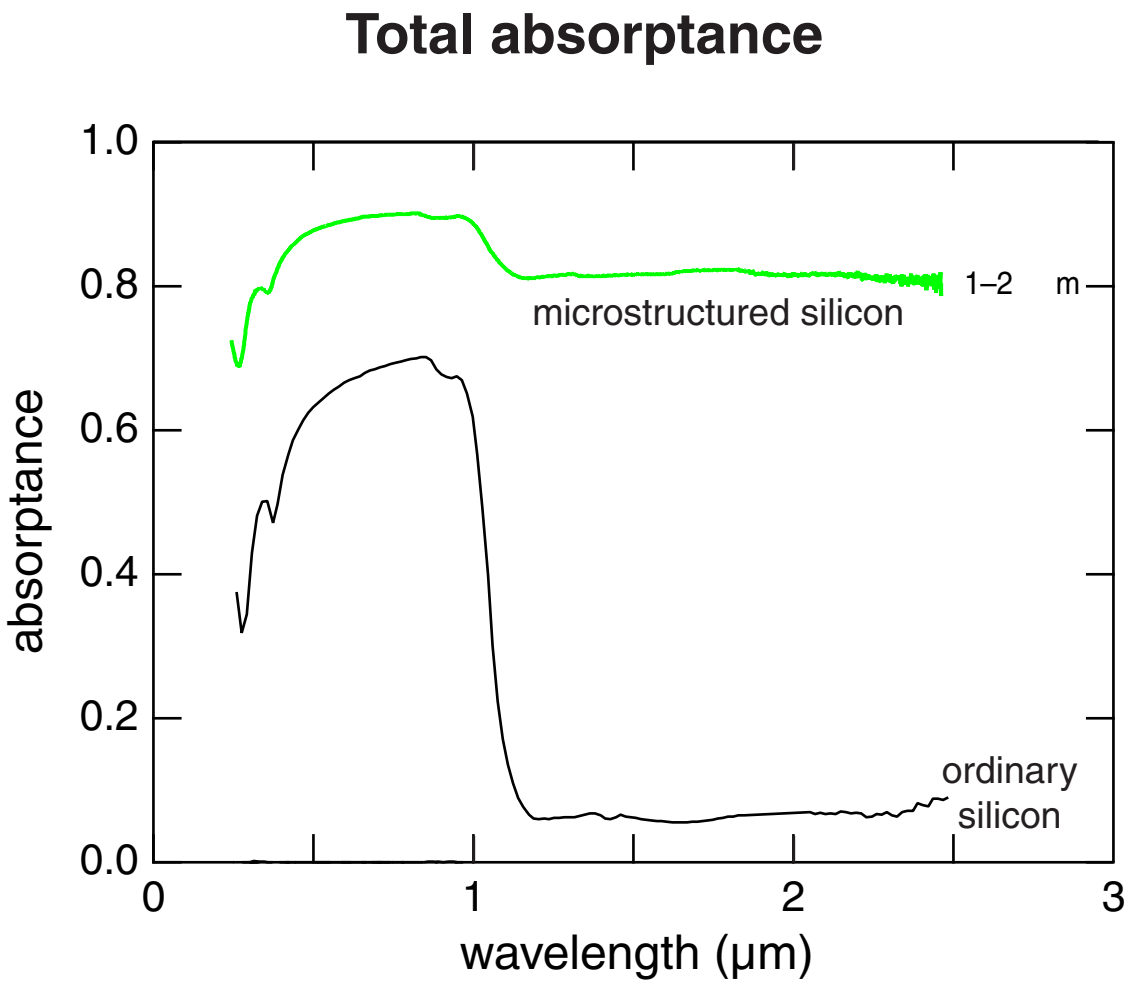


# *Microstructured silicon*

## Total integrated transmittance



# *Microstructured silicon*



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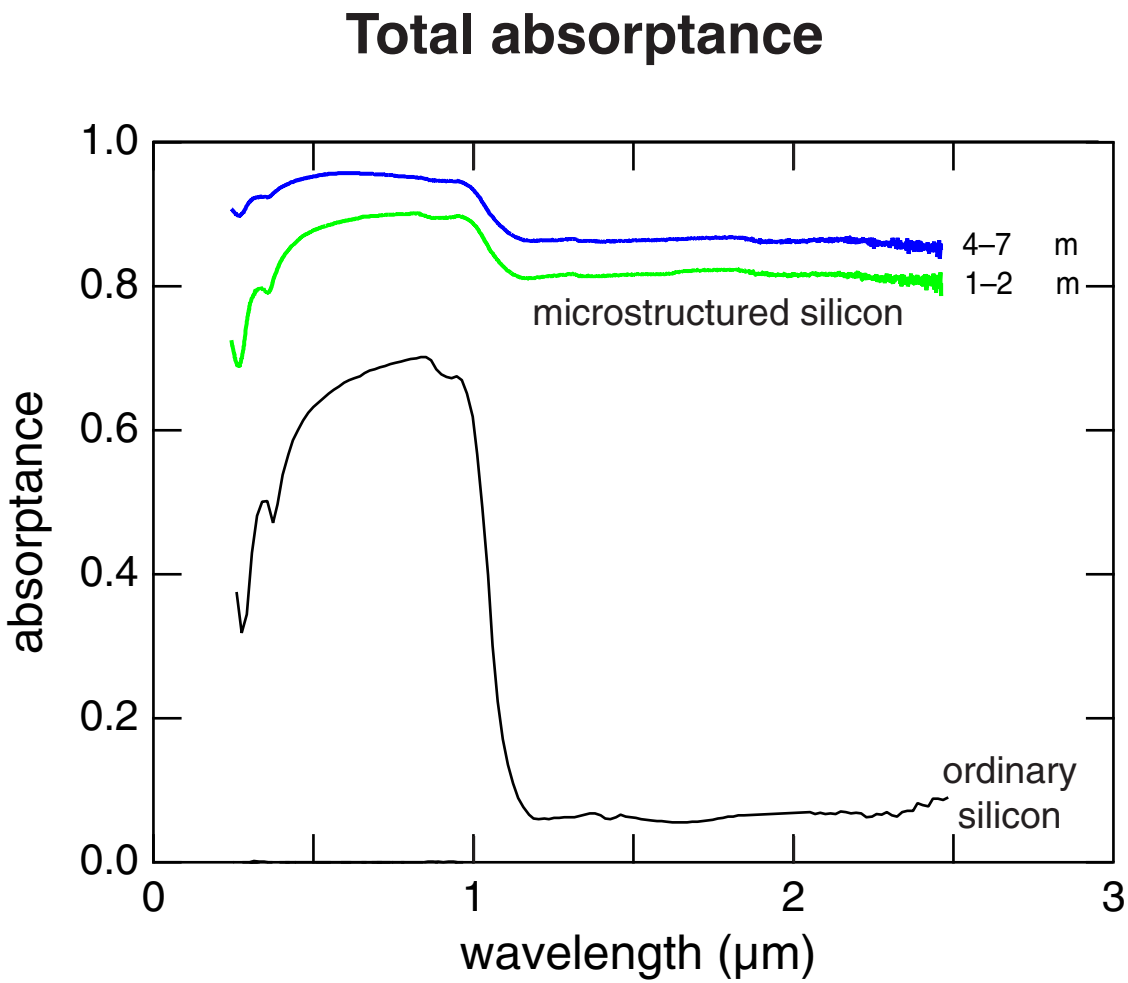

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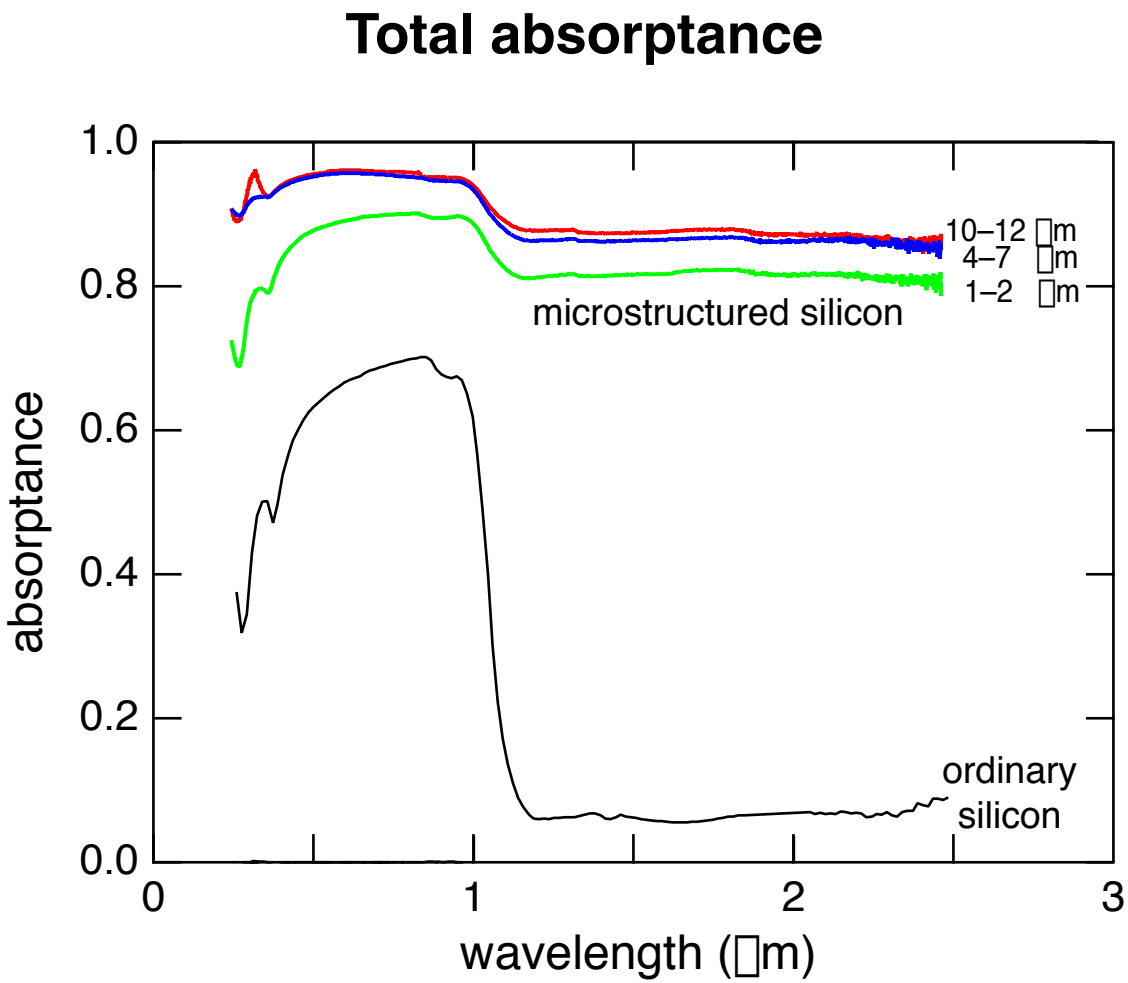
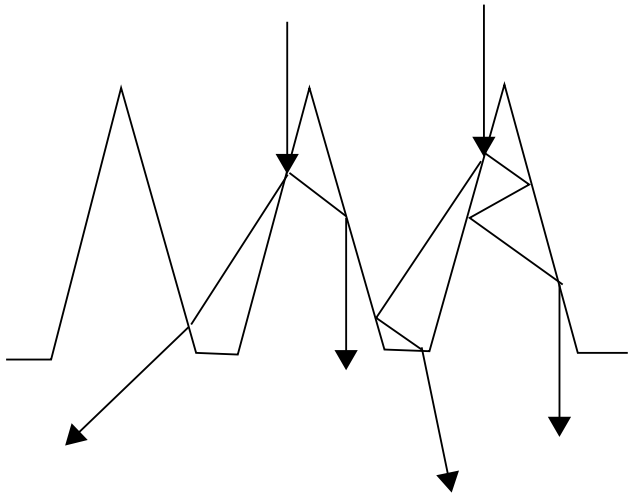
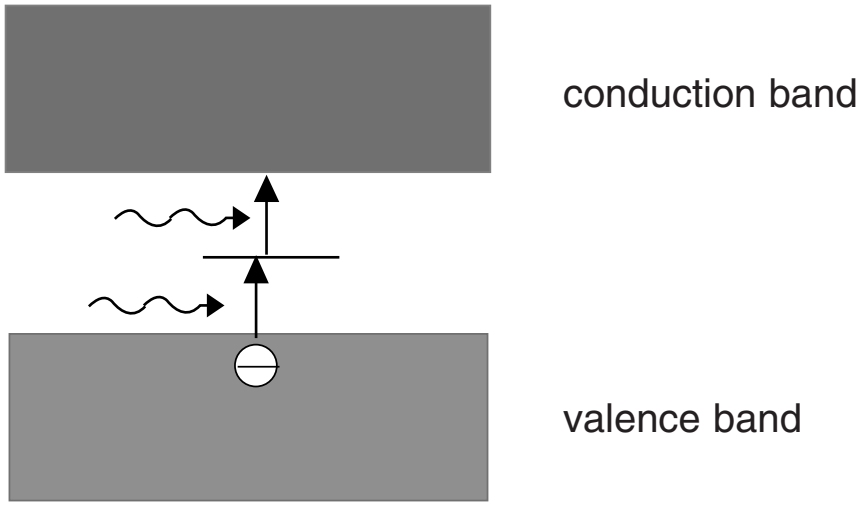


**What causes the absorption?**

# *Multiple reflections*

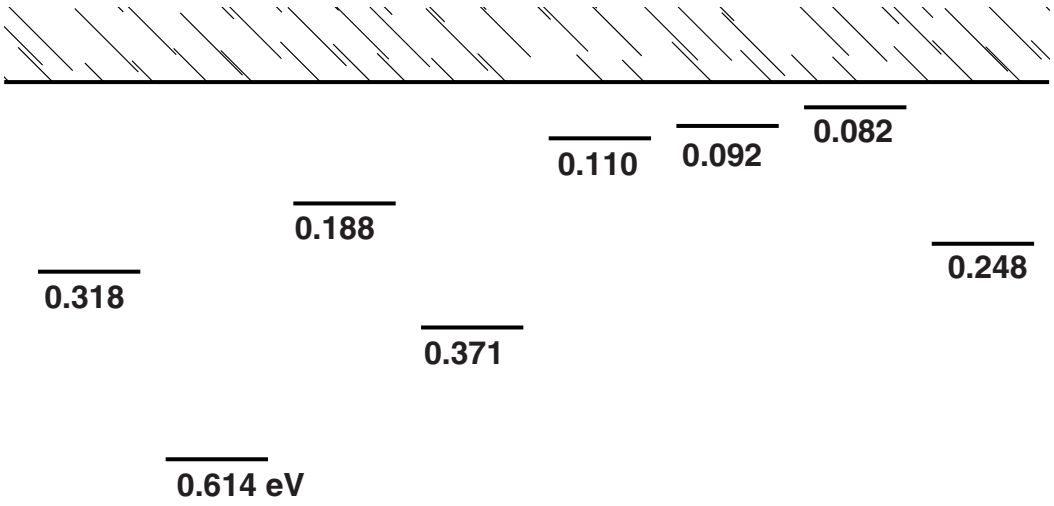


# *Below-band gap absorption*




**States in band gap allow subgap absorption**

# Sulfur energy levels

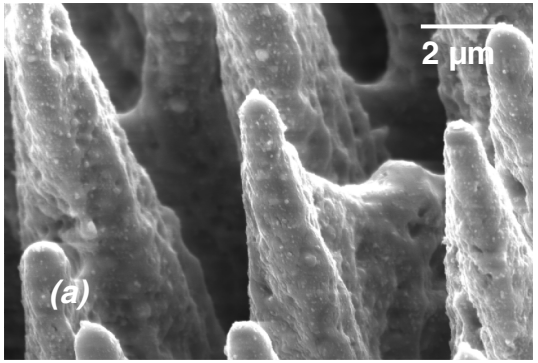



*Janzén et al. Phys. Rev. B* **29**, *1907 (1984)*

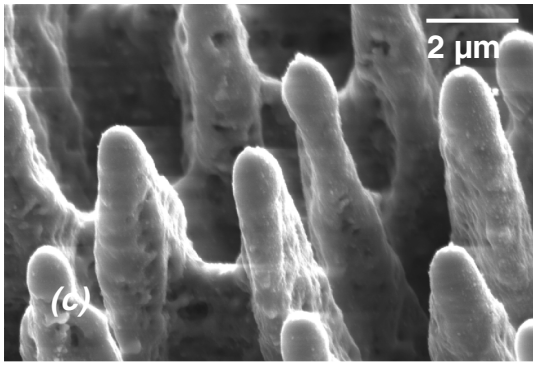
# *Below-band gap absorption*

**Anneal microstructured surface in vacuum ($10^{-7}$ torr) at 910°C for 3 hours**

# *Below-band gap absorption*




**before anneal**




**after anneal**

# *Below-band gap absorption*

**SIMS: S, F content decreases roughly twofold**

# *Below-band gap absorption*

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**Ion channeling: structural defects persist**

# *Below-band gap absorption*

**SIMS: S, F content decreases roughly twofold**

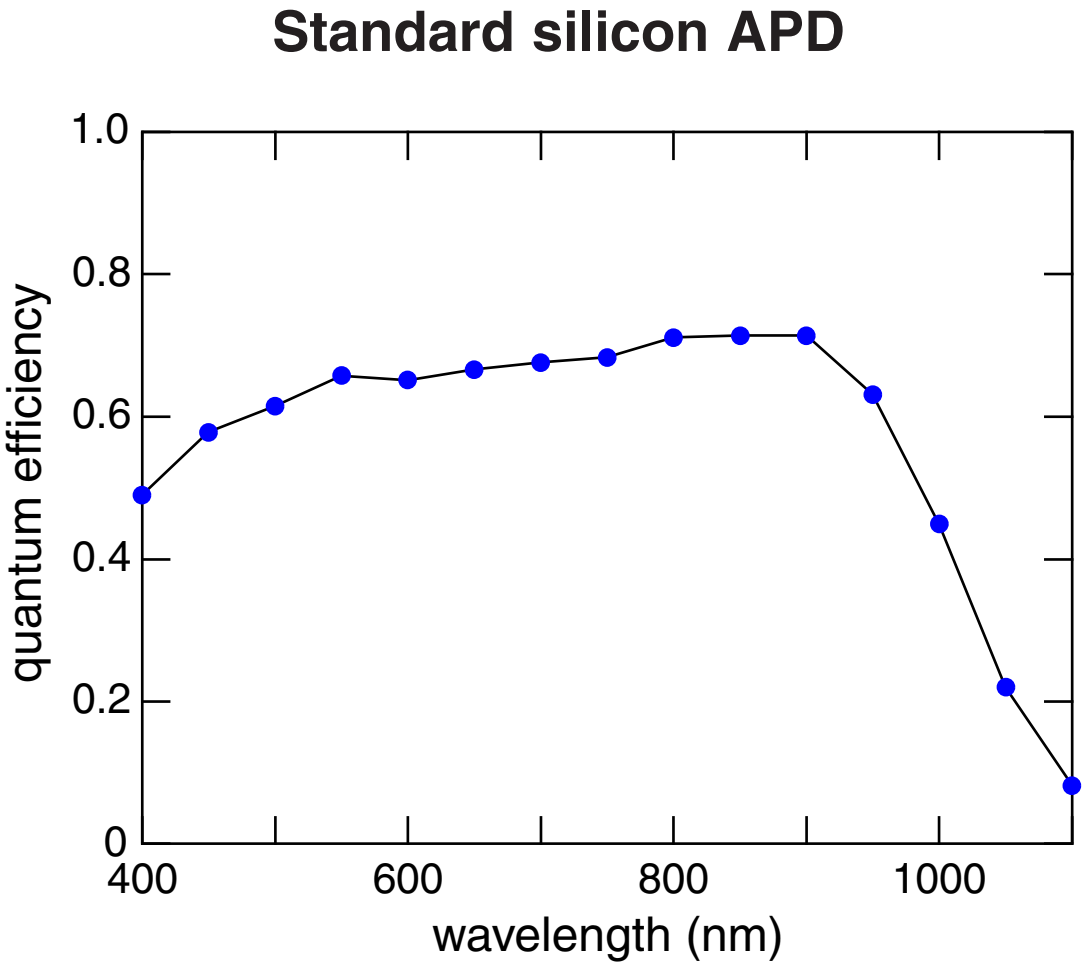
**Ion channeling: structural defects persist**

**Absorptance:**

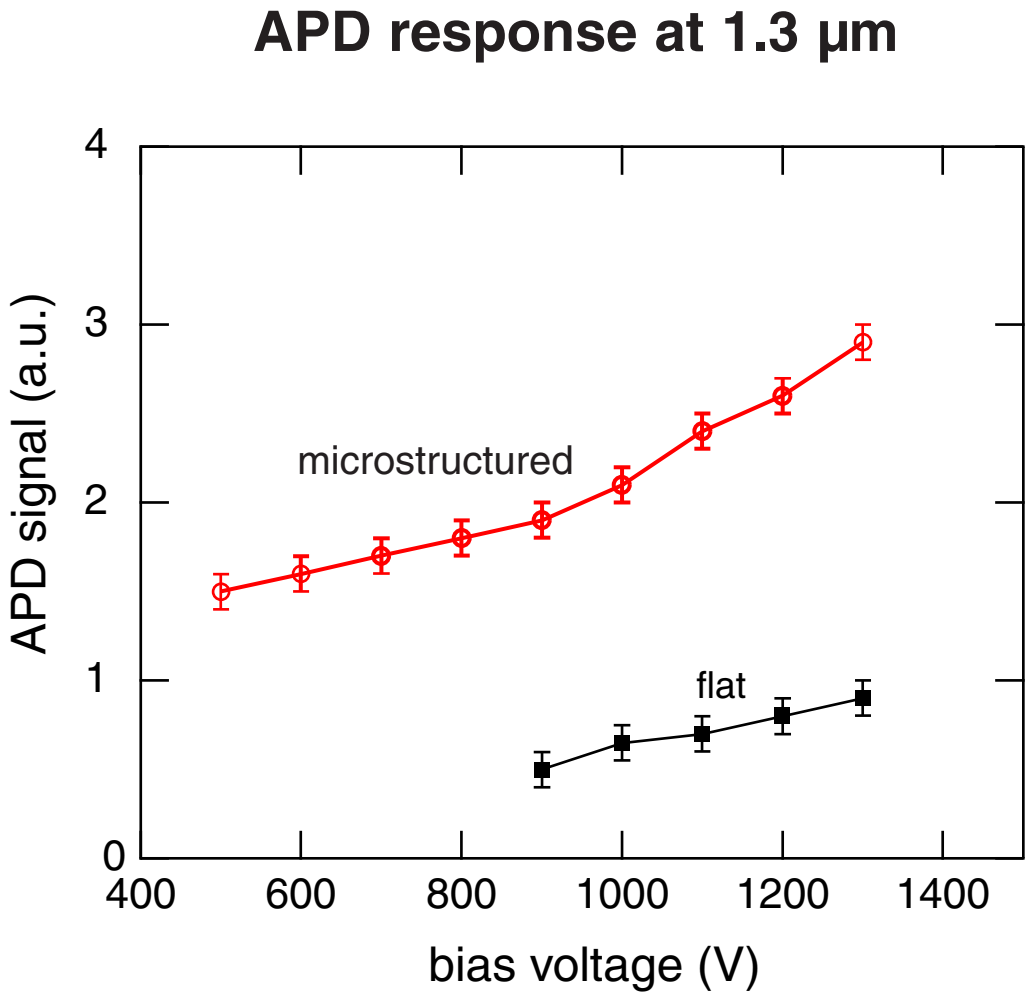
- **visible basically unchanged**
- **subgap decreases roughly twofold**

# Below-band gap photocurrent

# *Below-band gap photocurrent*



# *Below-band gap photocurrent*



# *Conclusions*

Material characterization:

- Mostly crystalline with structural and chemical defects

Optical properties:

- Unprecedented strong broadband absorptance (UV to IR)
- Below-band gap absorptance from impurities, multiple reflections

Photovoltaic properties:

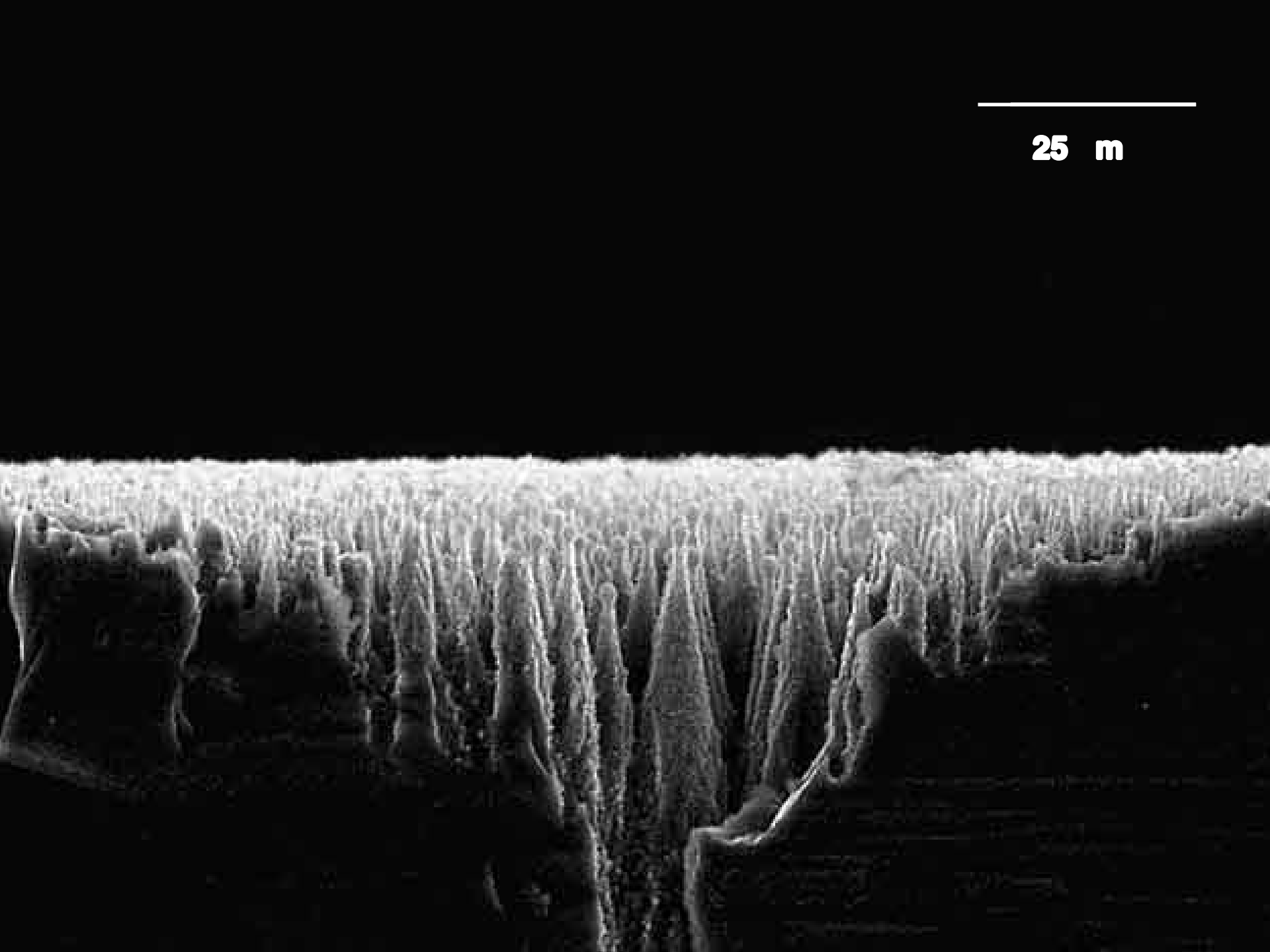
- More than 3-fold QE increase at 1.06 μm, 1.33 μm

# Acknowledgements:

**Collaborators:**
**Richard Farrell, Prakash Gothoskar, Arieh Karger (RMD)**

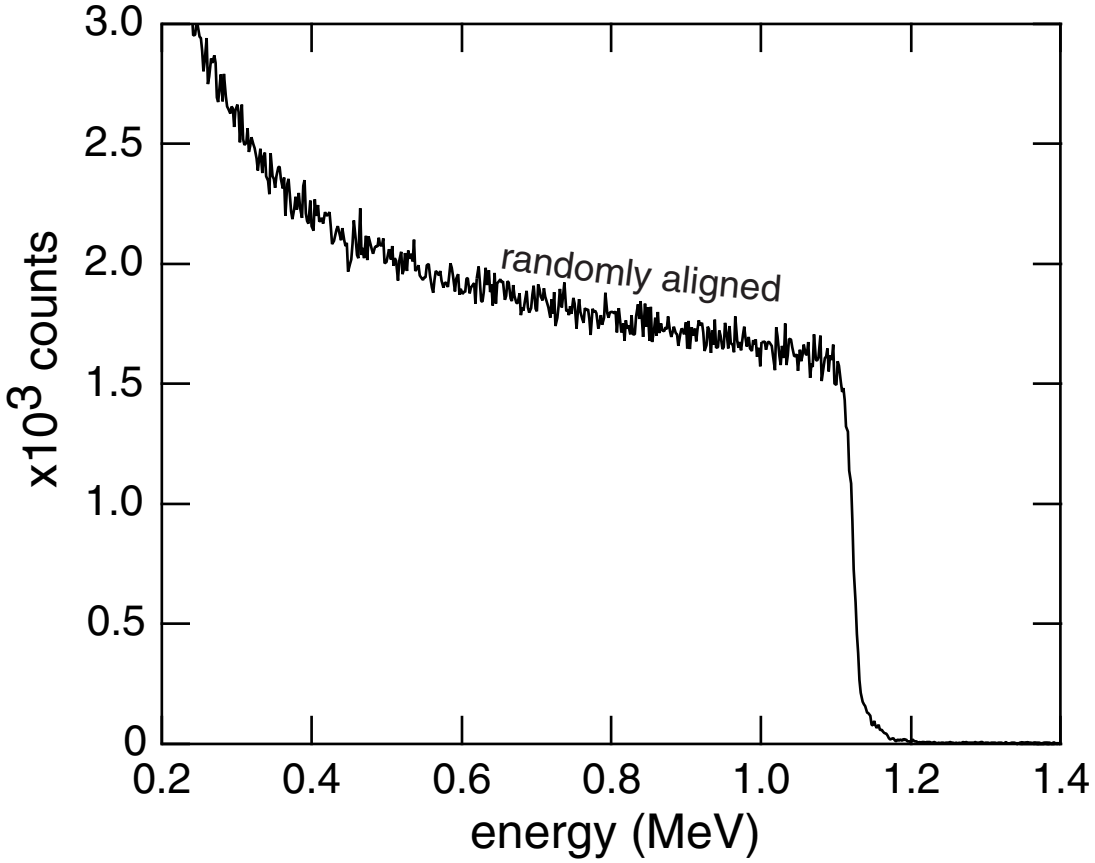
**Assistance:**
**Joseph Chen, John Chervinsky, Tom Mates, Dawen Pang**

**Discussion:**
**Michael Aziz, Cynthia Friend, Frans Spaepen, William Paul, Mazur Group**


25 m

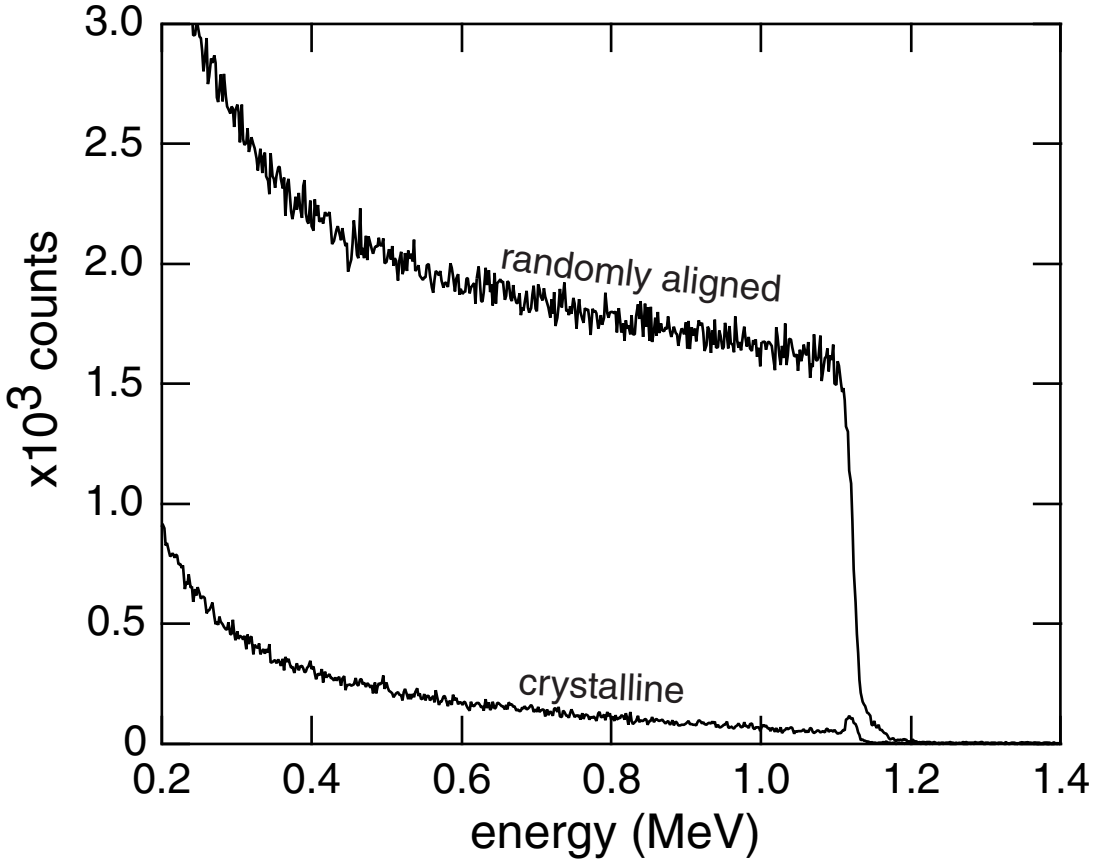
# *Structural properties*

## Ion channeling



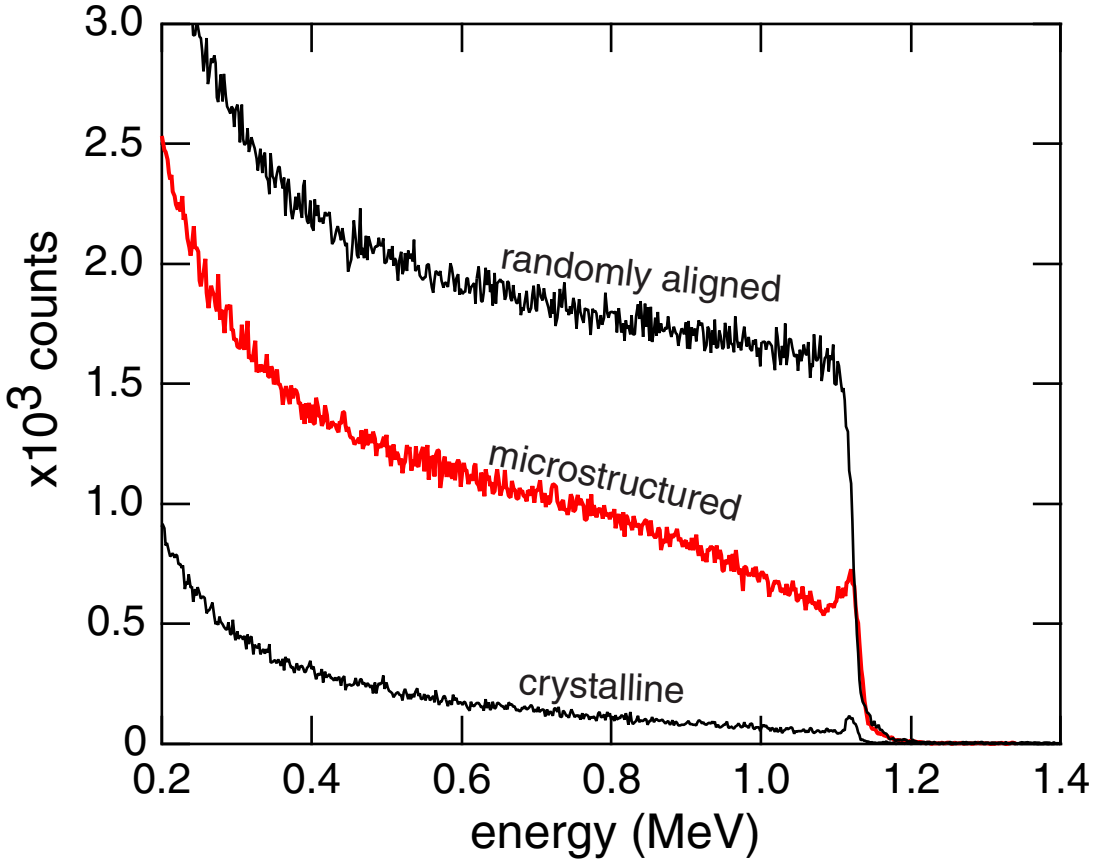
# *Structural properties*

## Ion channeling

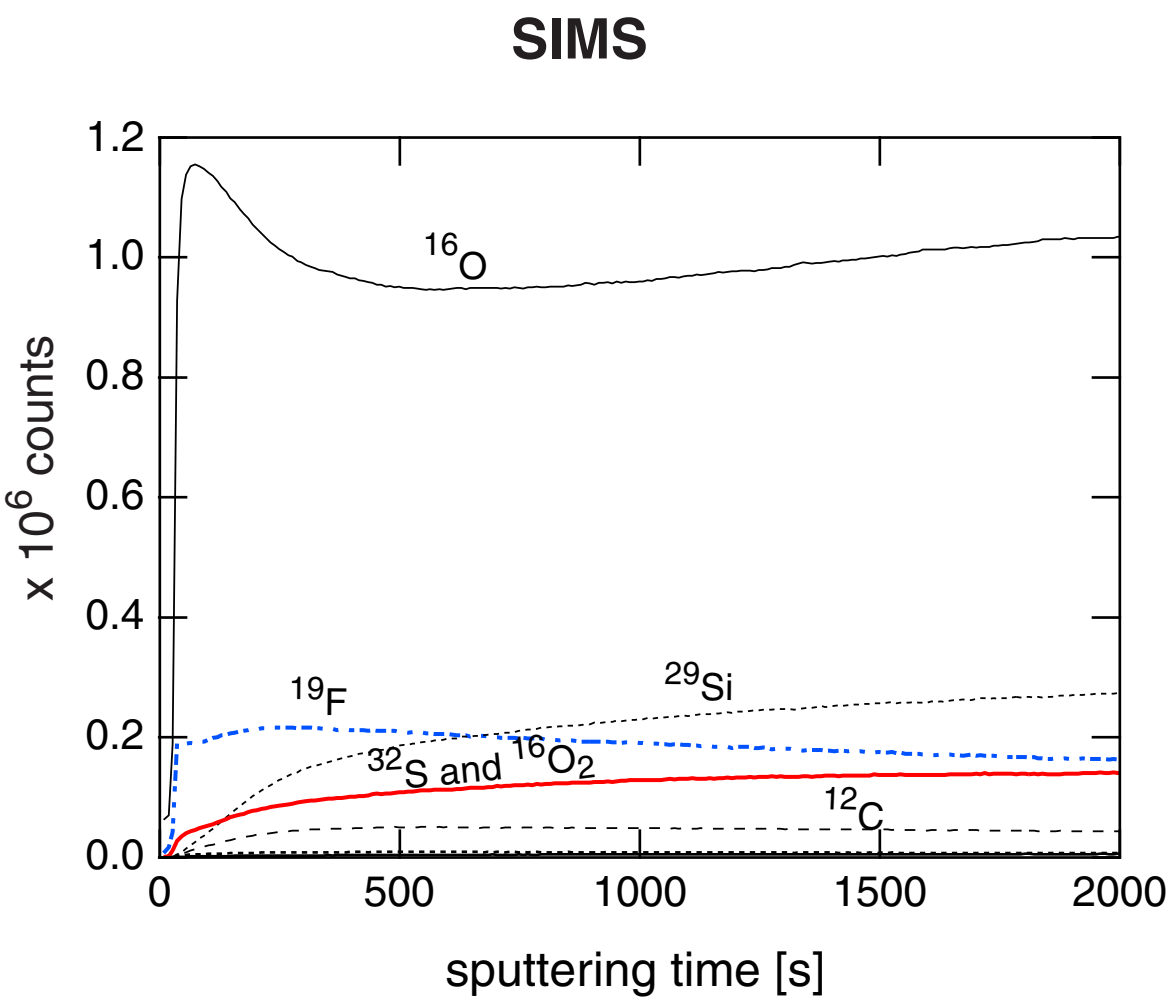


# *Structural properties*

## Ion channeling



# Chemical composition



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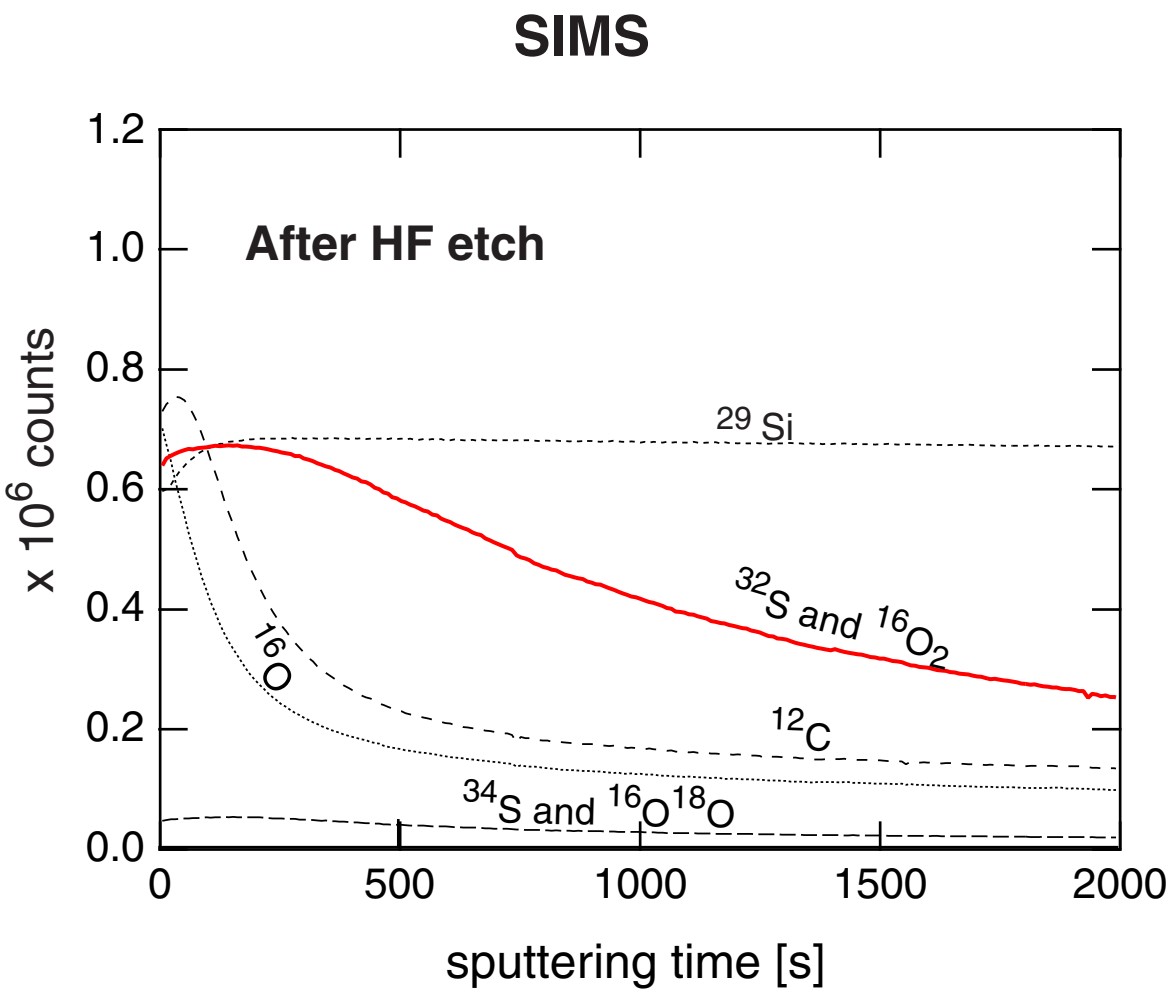
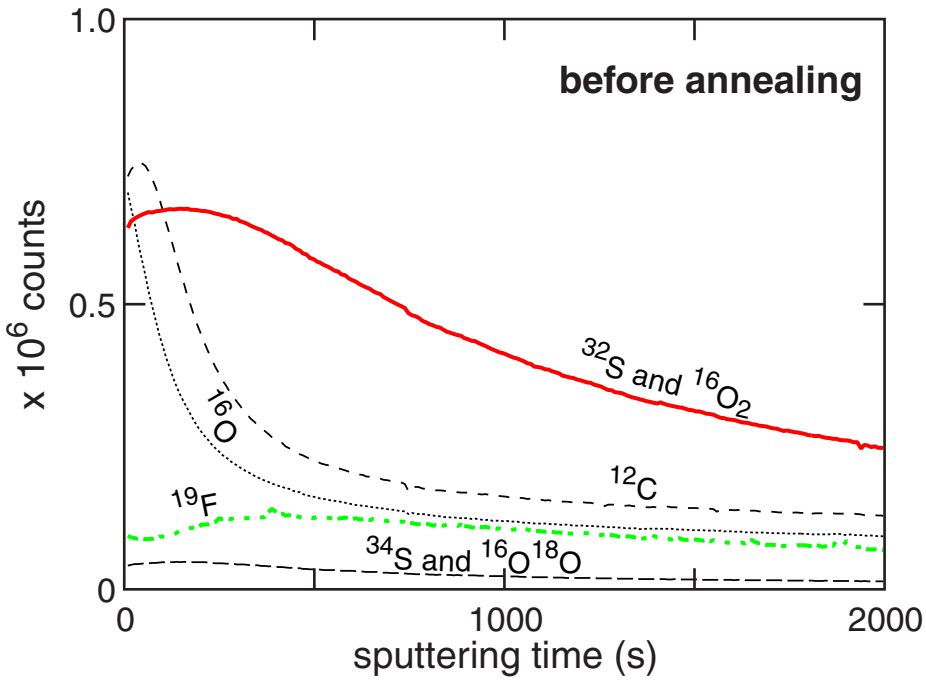
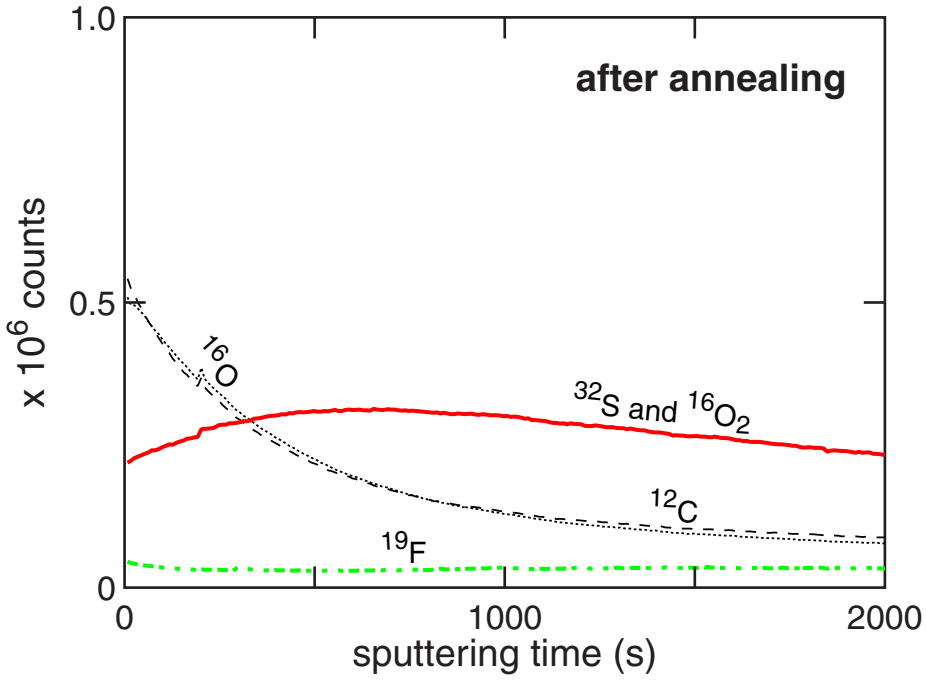


# Below-band gap absorption



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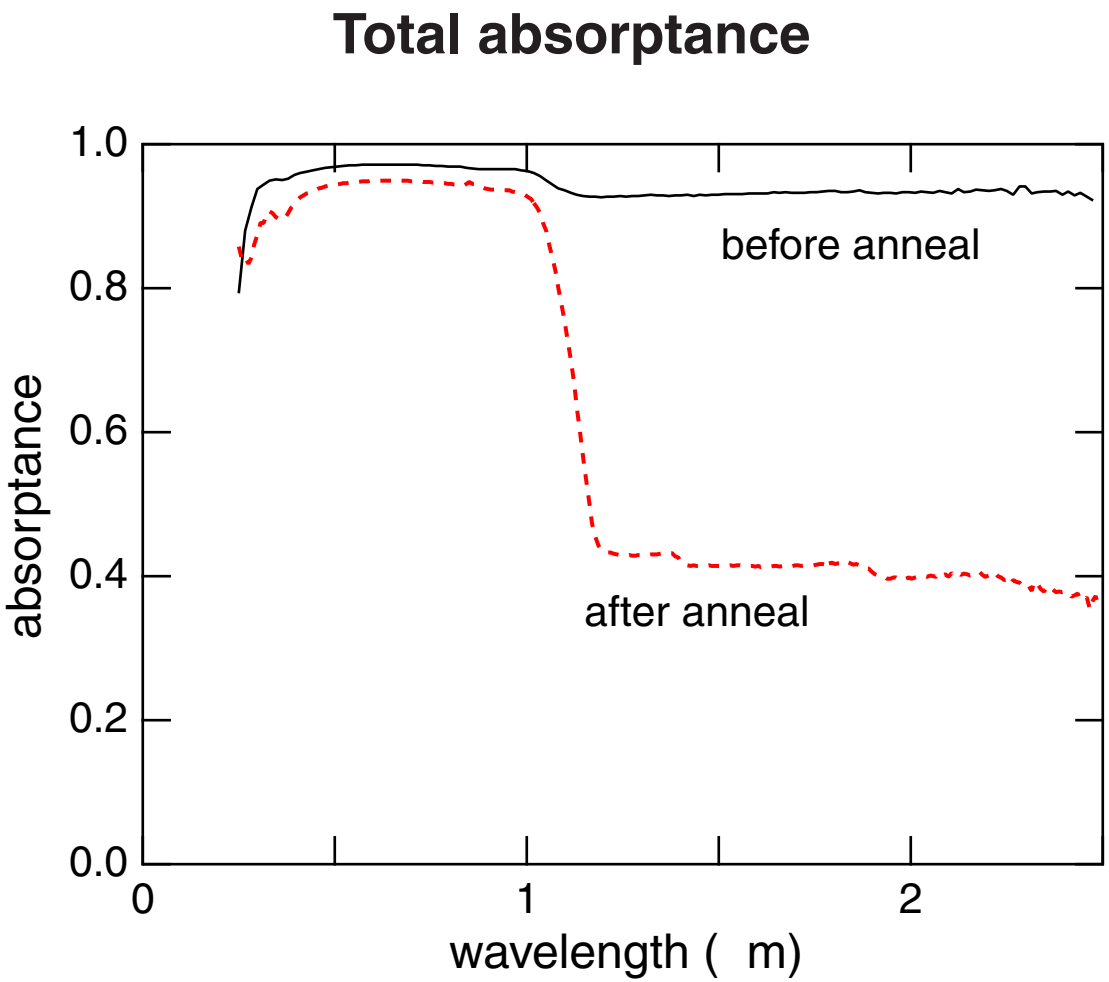

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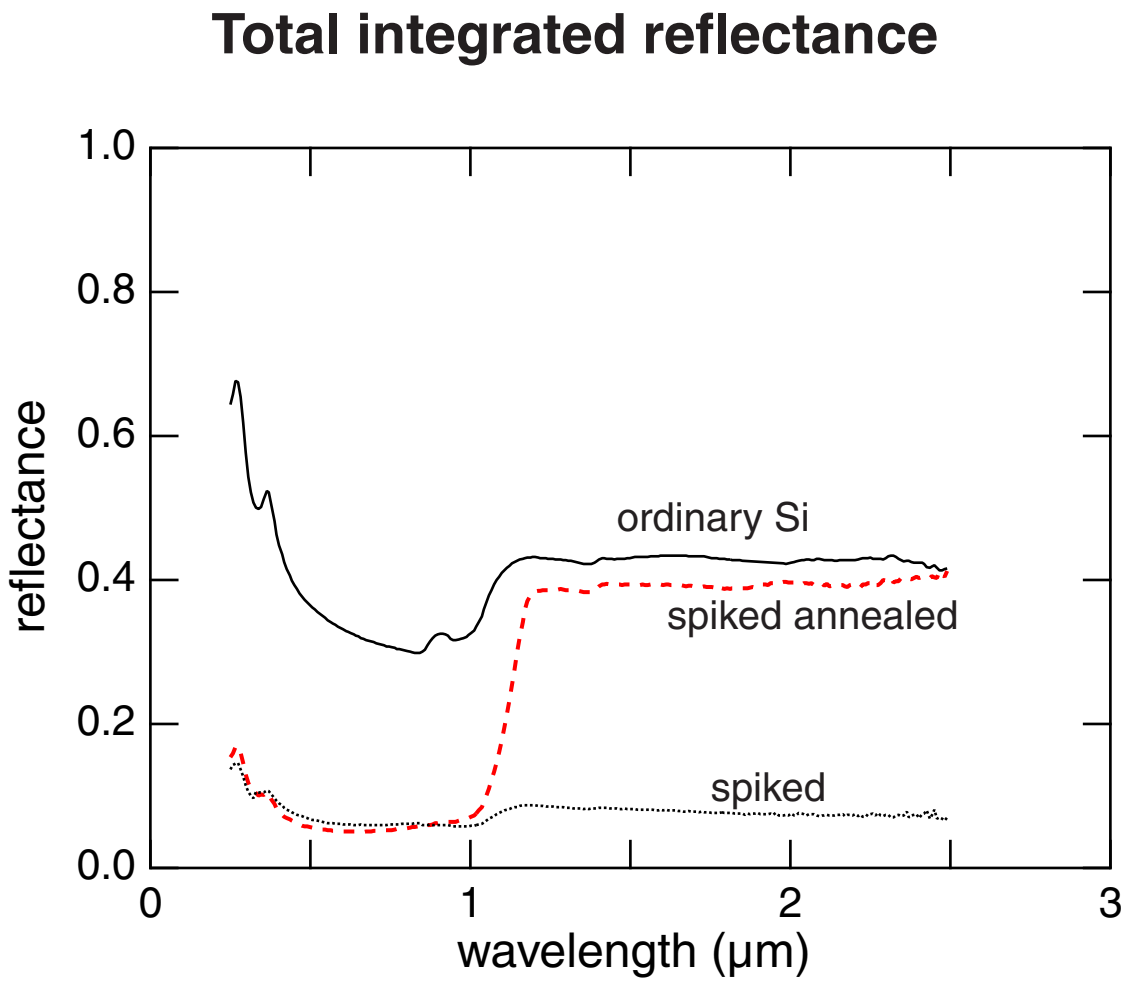

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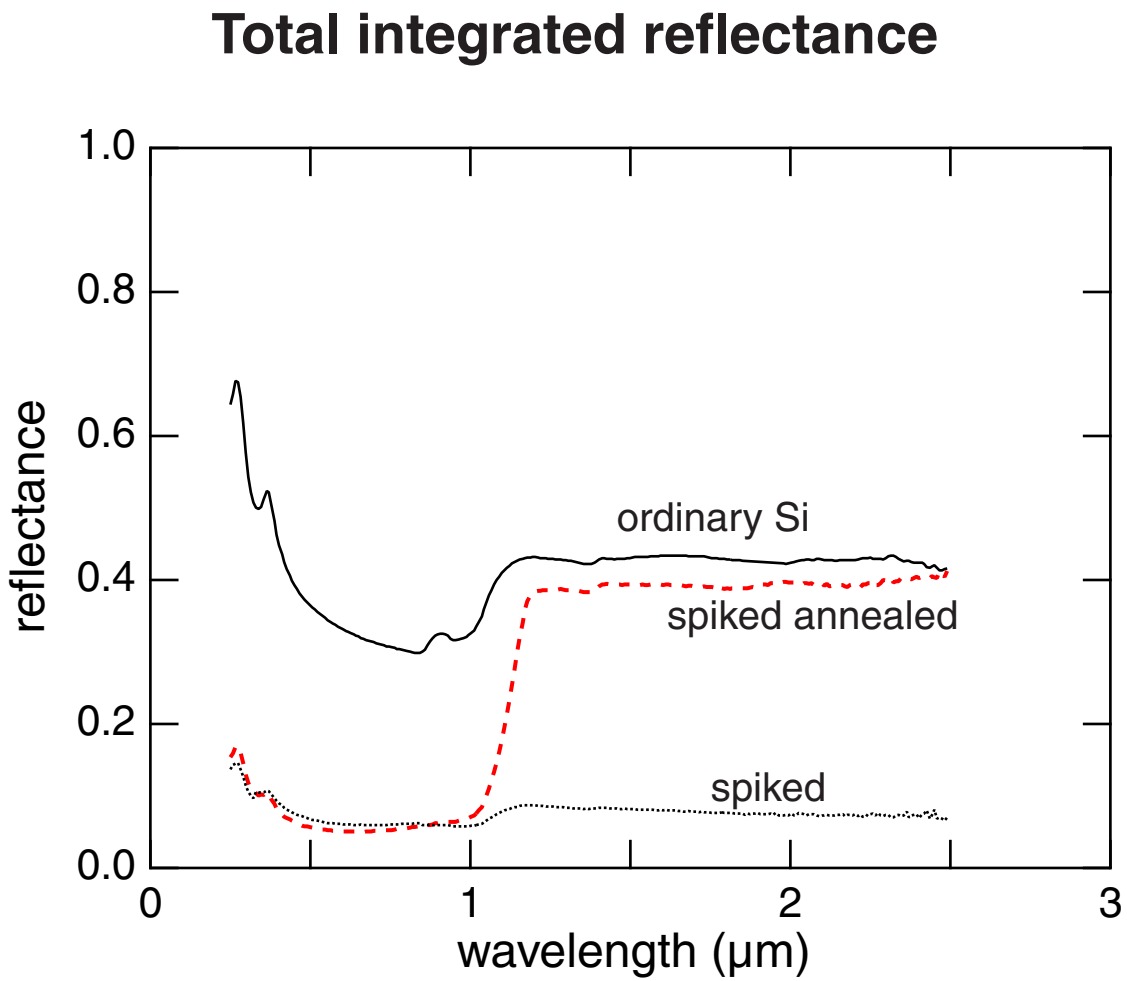
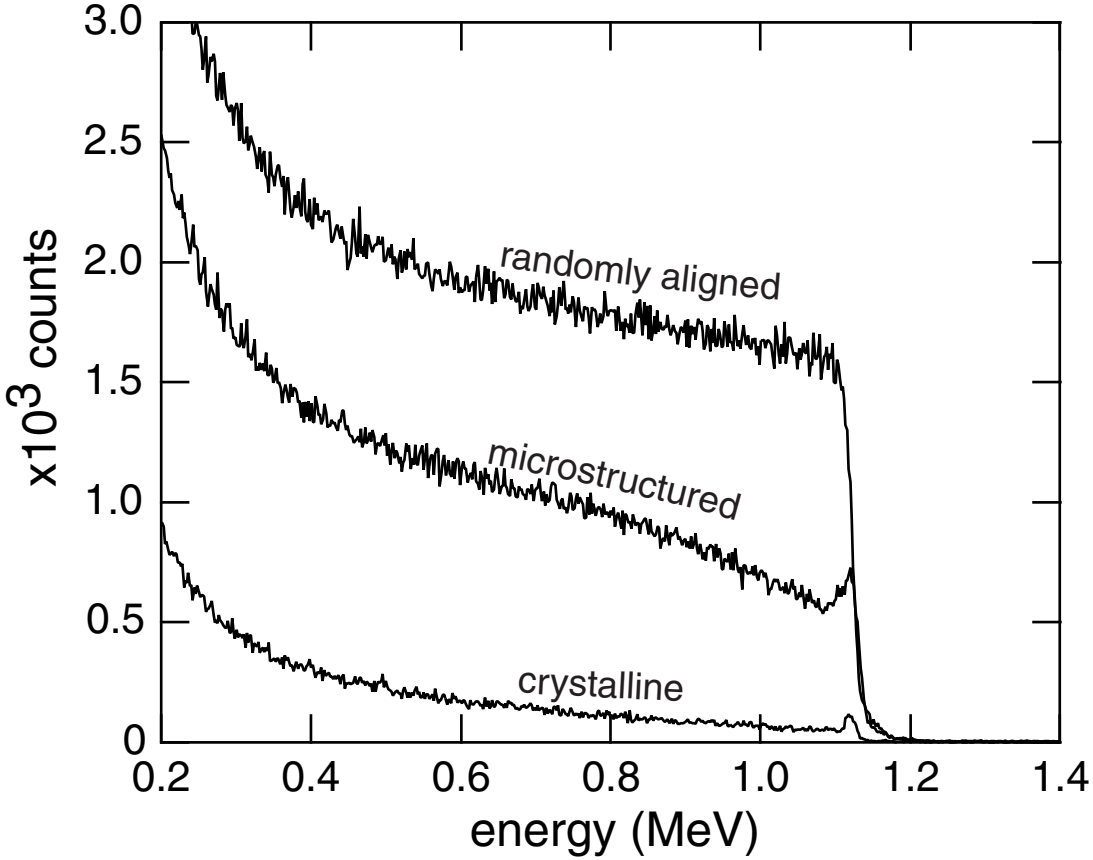


# *Below-band gap absorption*

## Ion channeling



# *Below-band gap absorption*

## Ion channeling