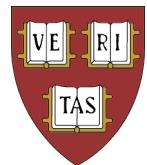


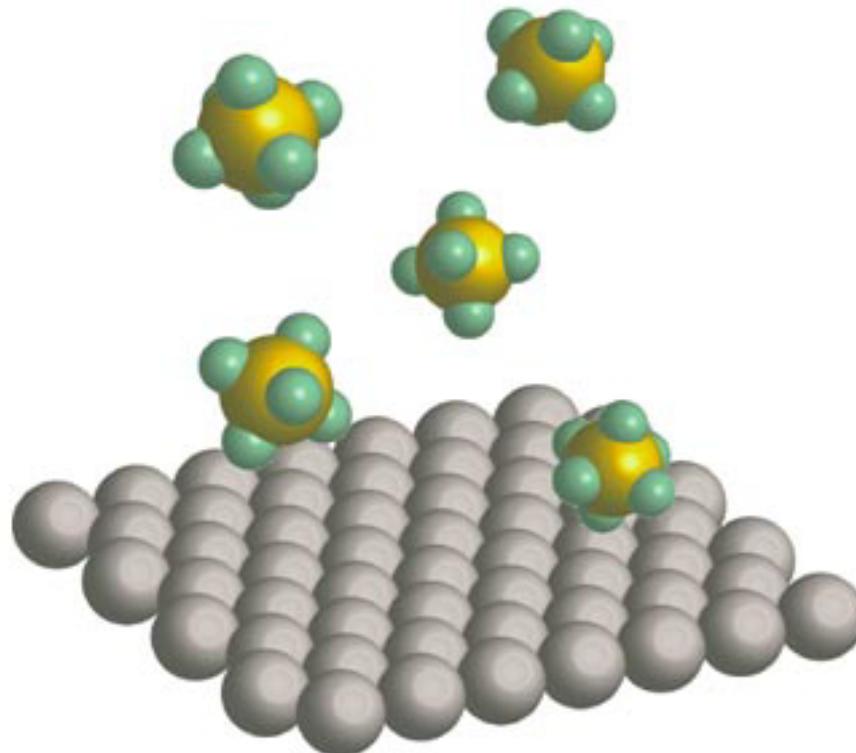
# **Below-band gap absorption in microstructured silicon**

**Claudia Wu, Catherine Crouch, Li Zhao,  
Jim Carey, Rebecca Younkin, Joshua Levinson,  
Eric Mazur**

**Harvard University**

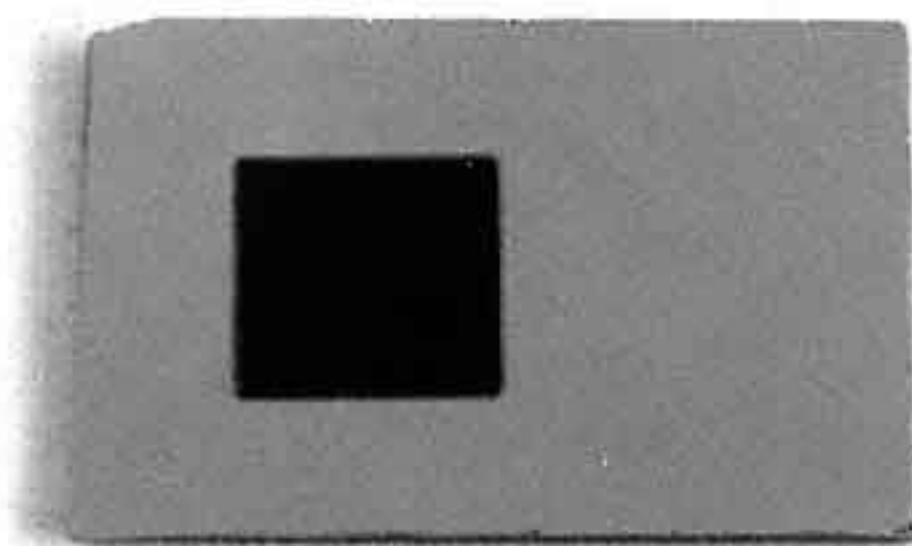


# *Microstructuring Silicon*



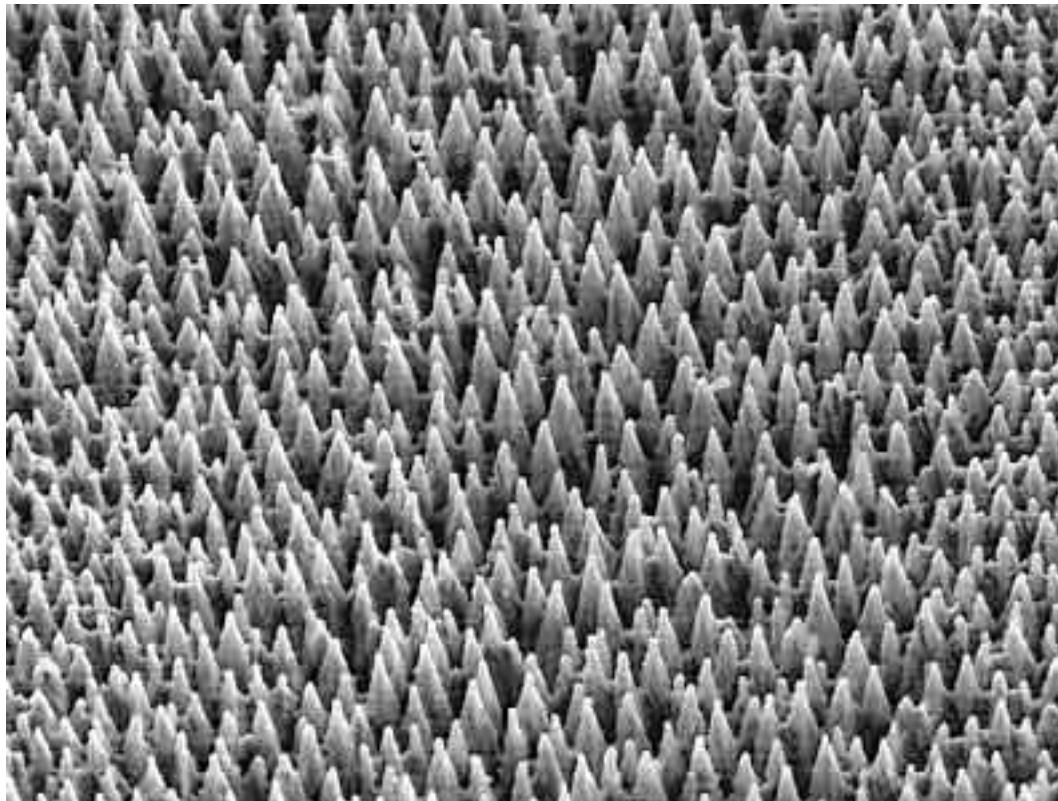
irradiate with 100 fs  $10 \text{ kJ/m}^2$

# *Black Silicon*



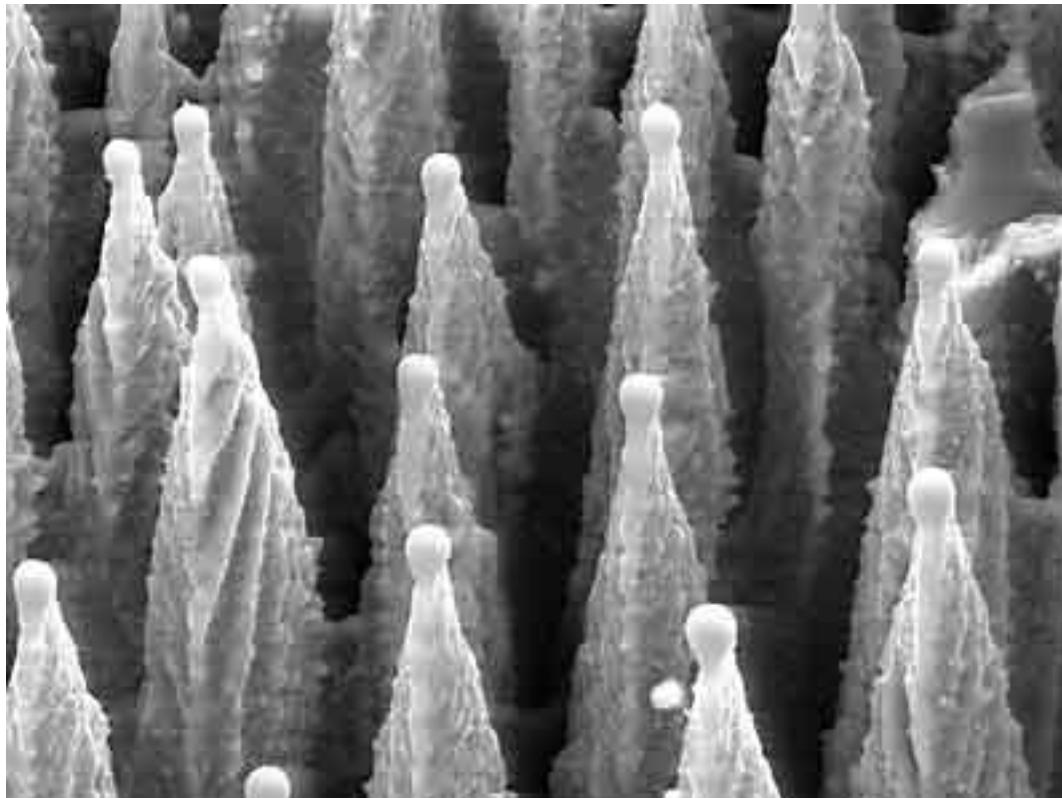
5 mm

# *Microstructuring Silicon*



20  $\mu\text{m}$

# *Microstructuring Silicon*



4  $\mu\text{m}$

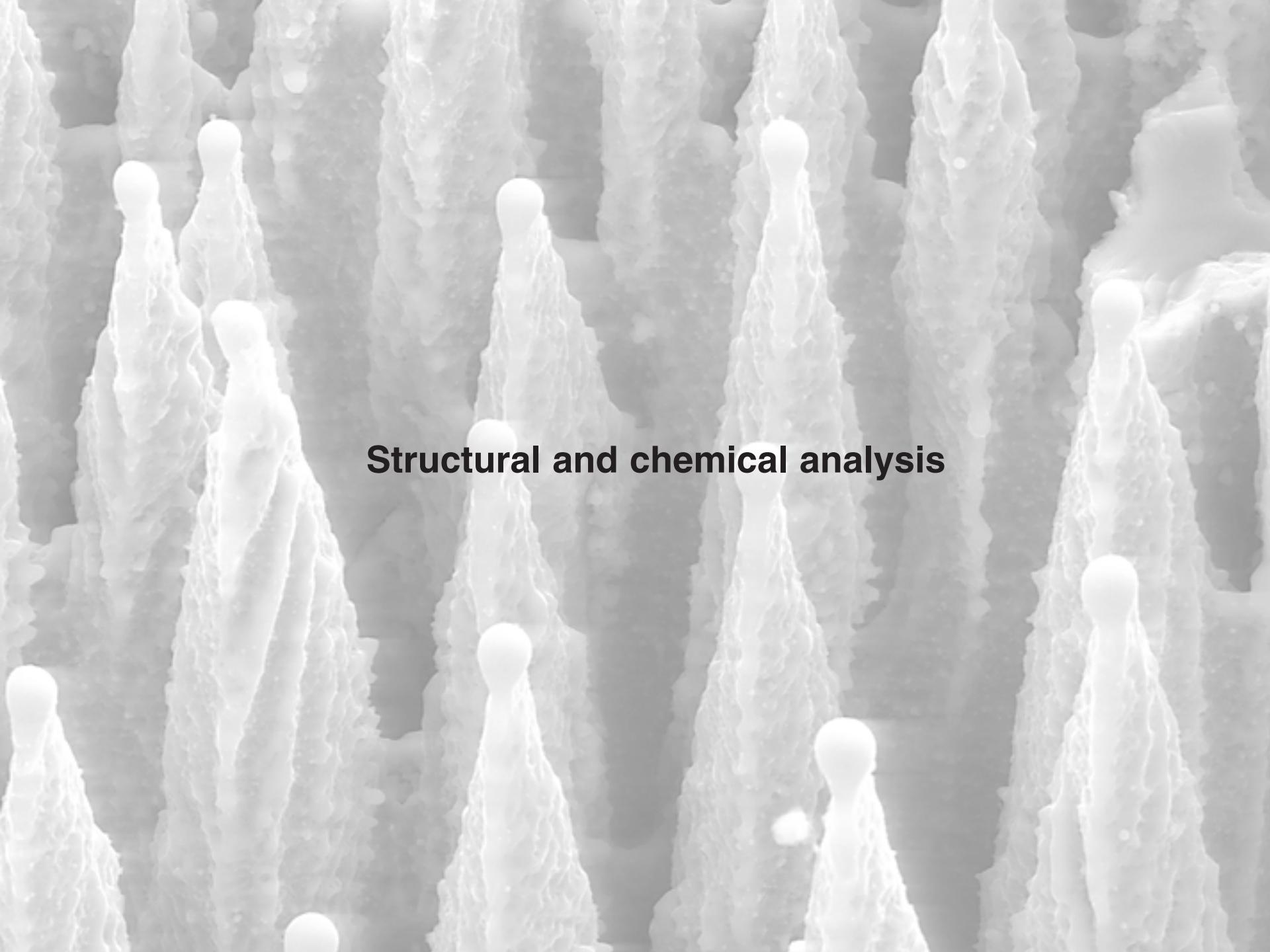
# Outline

I. Characterization of silicon microspikes

II. Optical properties

III. Below-band gap photocurrent

IV. Conclusion

A scanning electron micrograph (SEM) showing a highly textured surface. The surface features numerous vertical, elongated, and slightly wavy ridges that create a pattern of deep, narrow grooves between them. The ridges appear to have a fine-grained, somewhat porous texture. The lighting is bright, highlighting the ridges against a darker background.

**Structural and chemical analysis**

## *Structural properties*

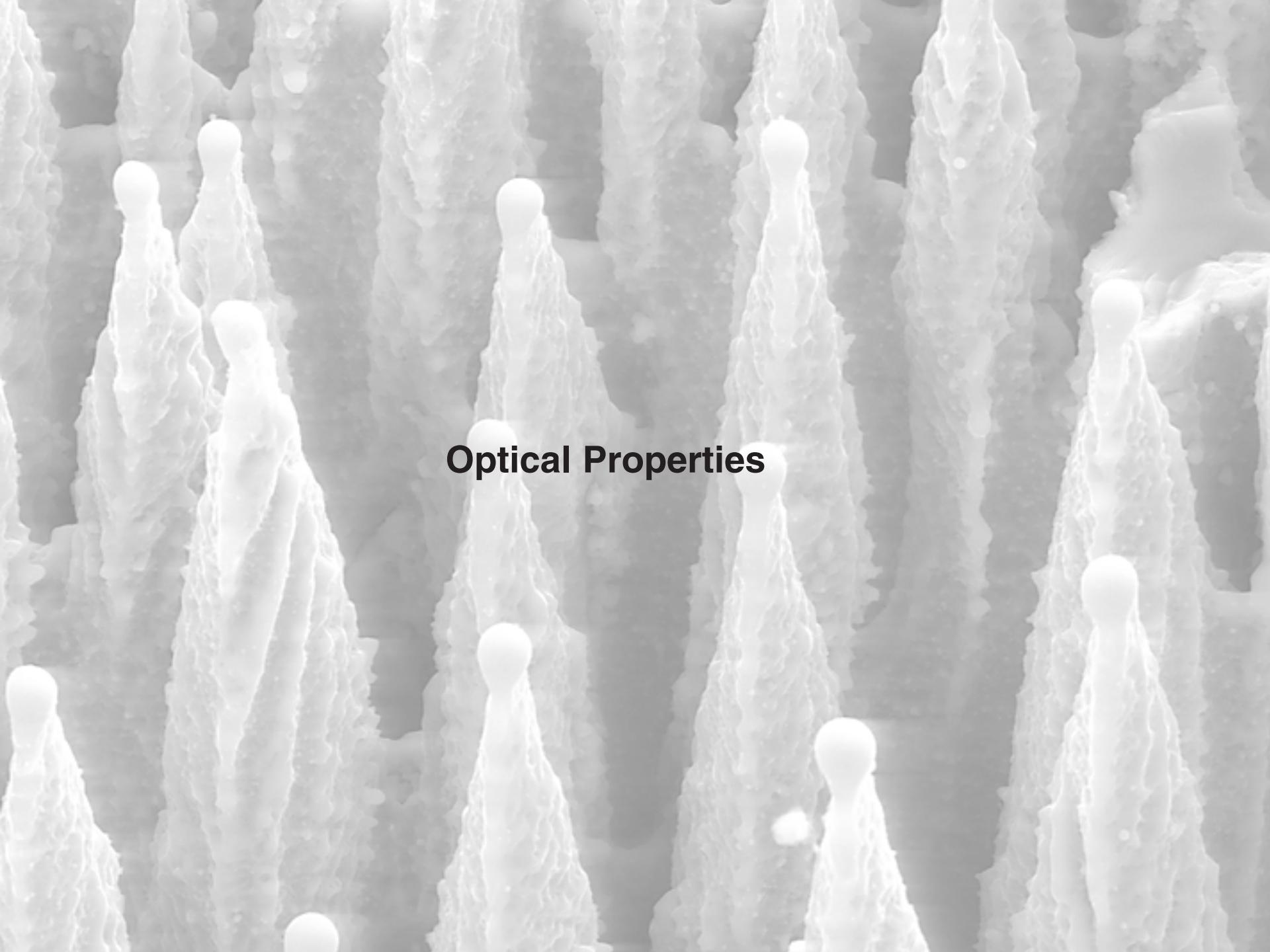
### **Ion channeling and electron backscattering**

- Microstructured silicon retains crystalline order
- High density of defects

# *Chemical analysis*

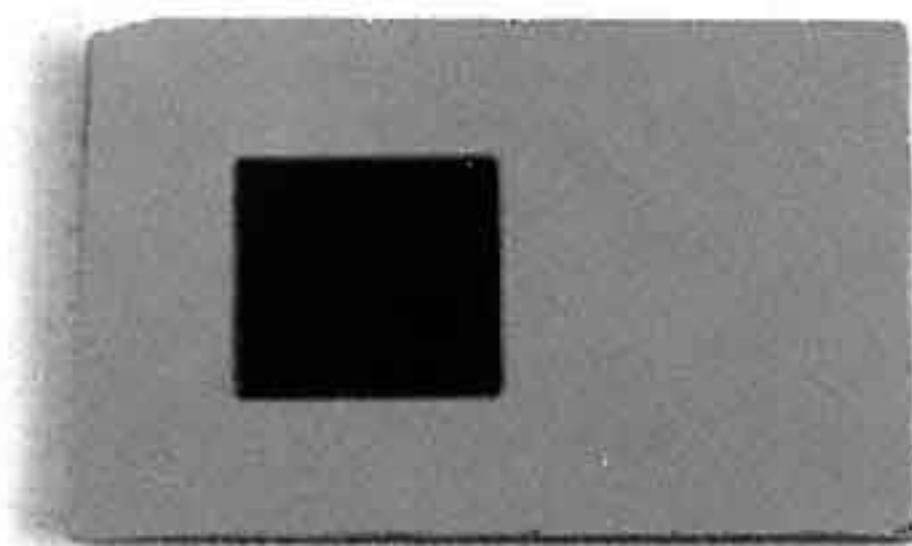
## **Secondary Ion Mass Spectrometry (SIMS)**

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



## Optical Properties

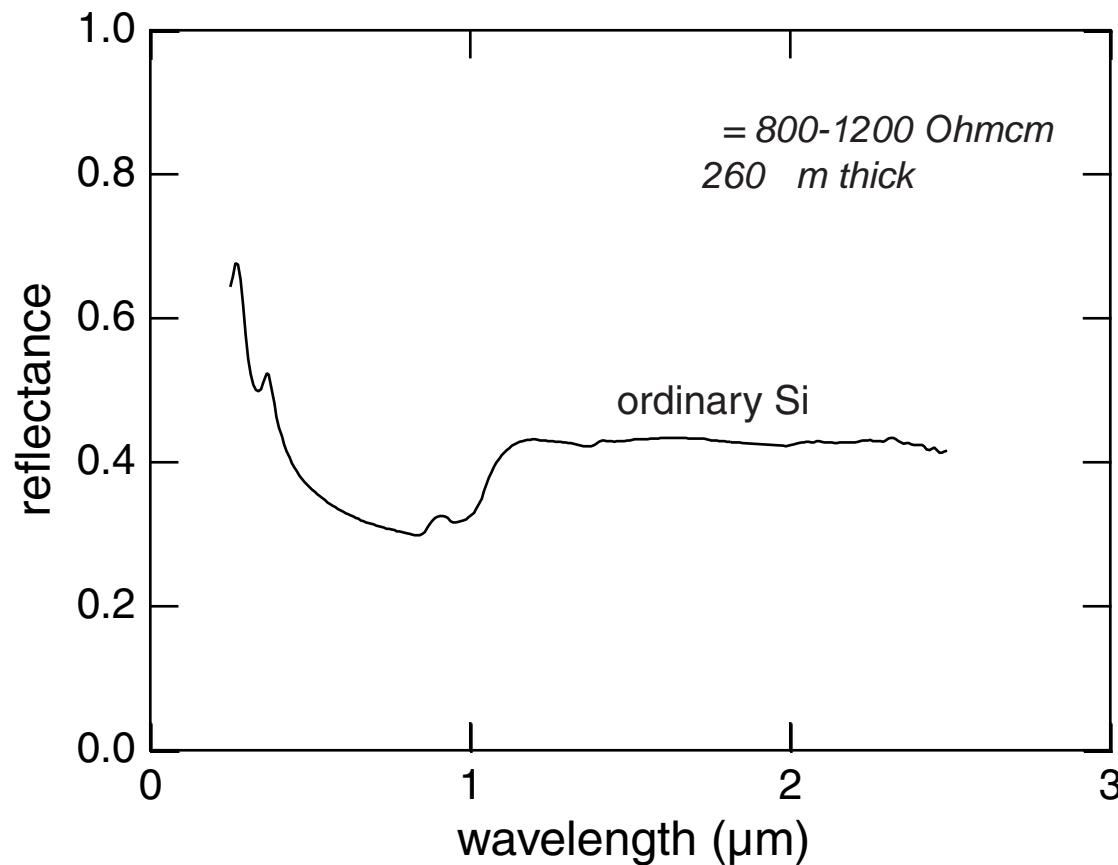
# *Black Silicon*



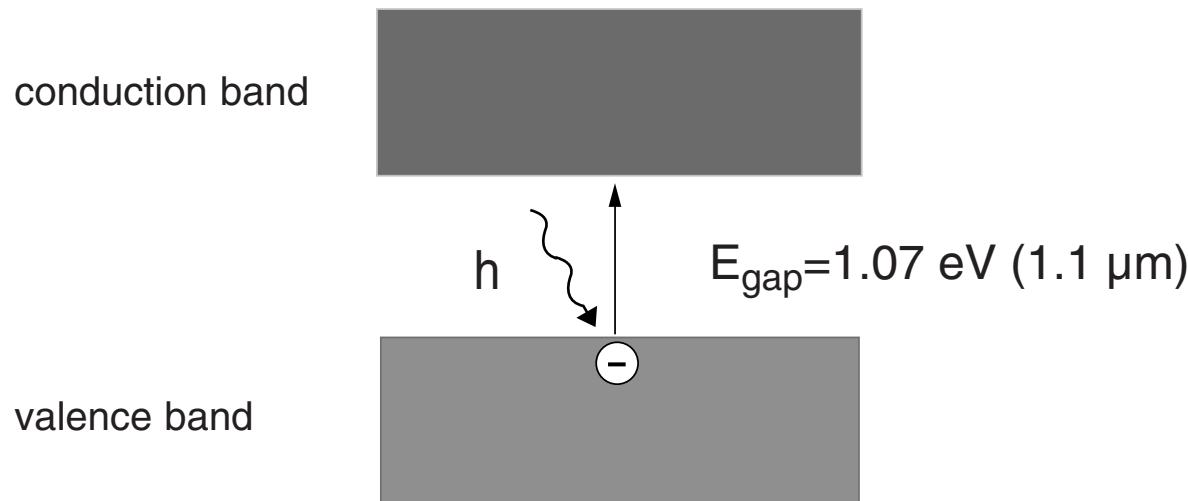
5 mm

# *Ordinary silicon*

## Reflectance



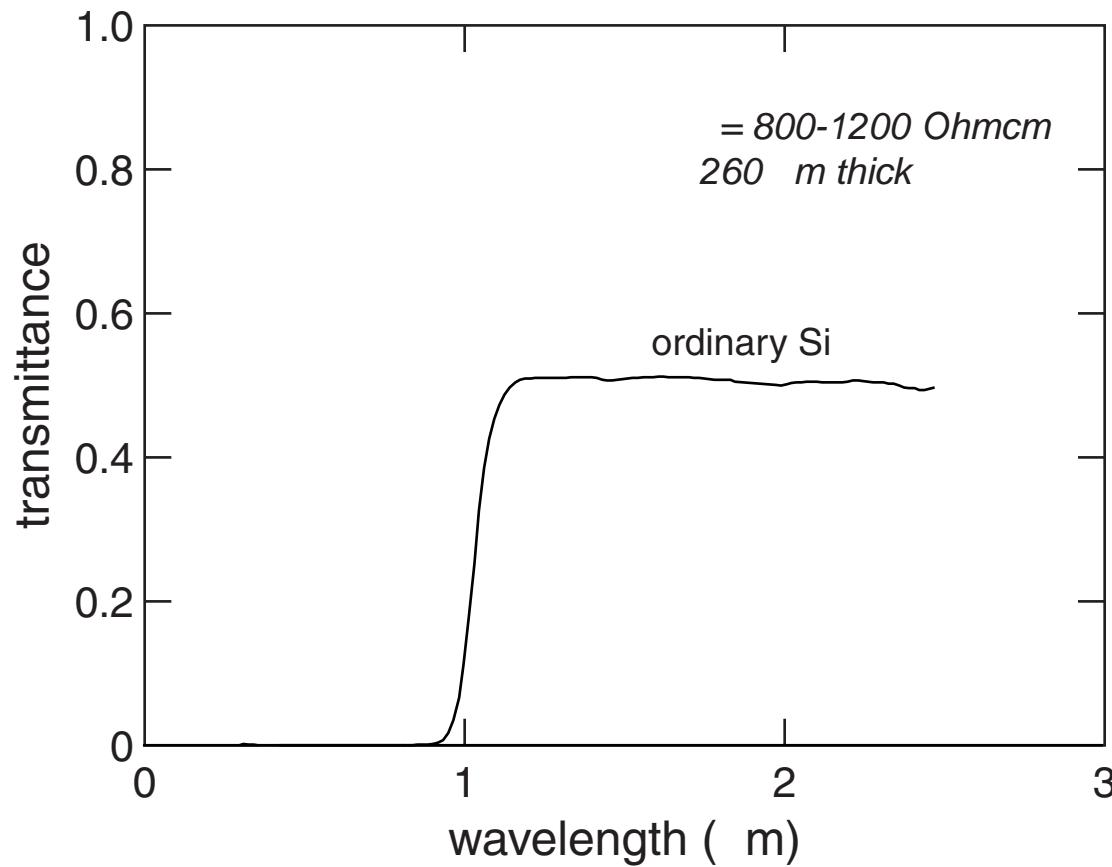
## *Ordinary silicon*



**Only wavelengths  $< 1.1 \mu\text{m}$  are absorbed**

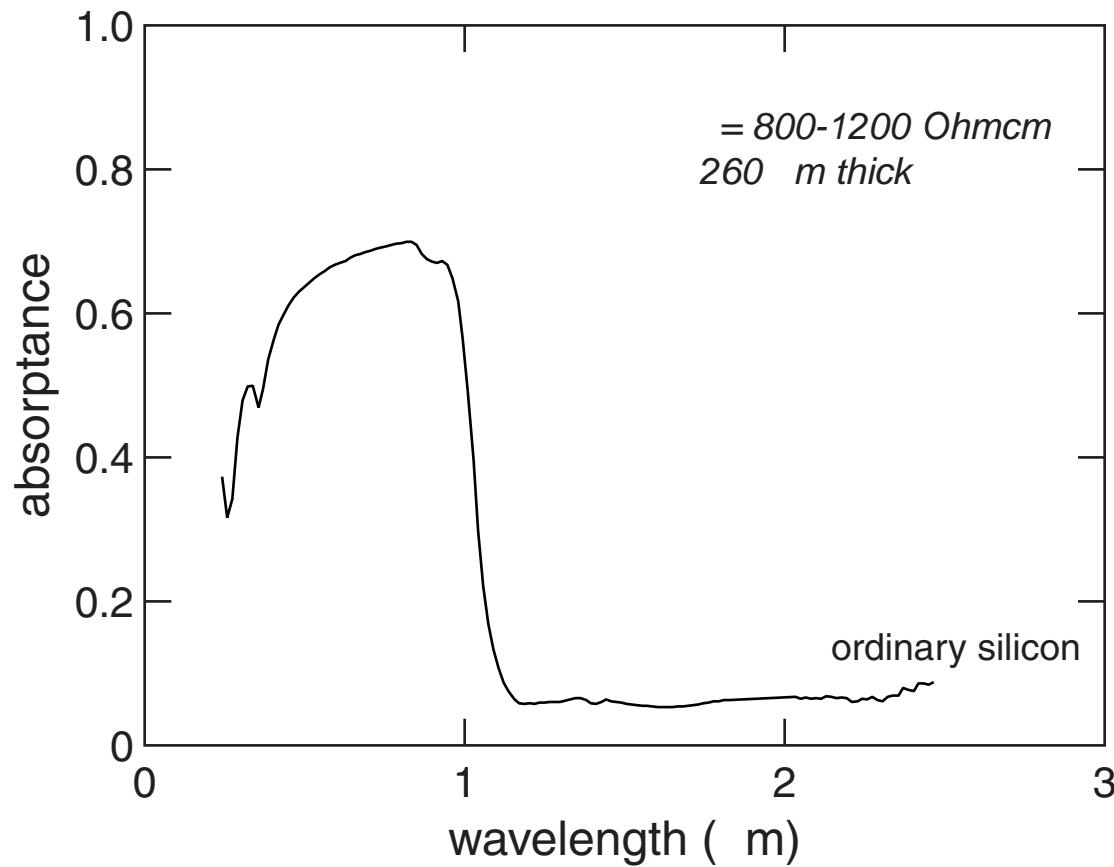
# *Ordinary silicon*

## Transmittance

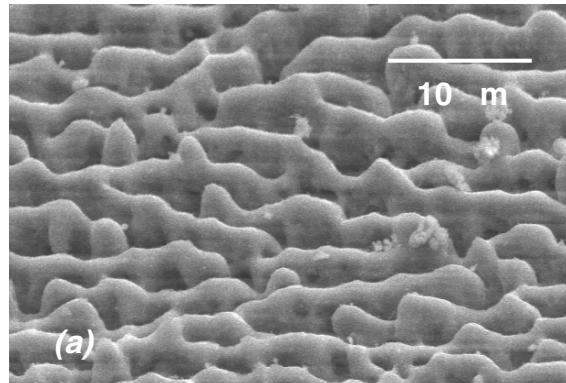


# *Ordinary silicon*

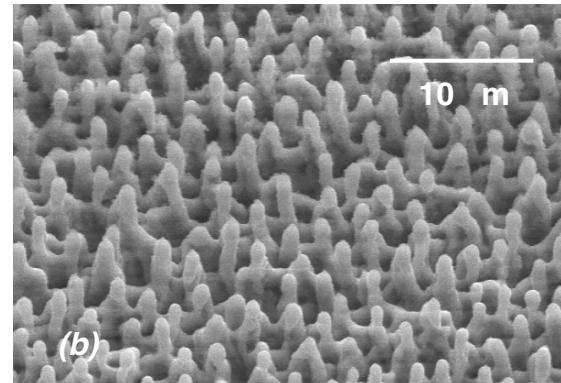
## Absorptance



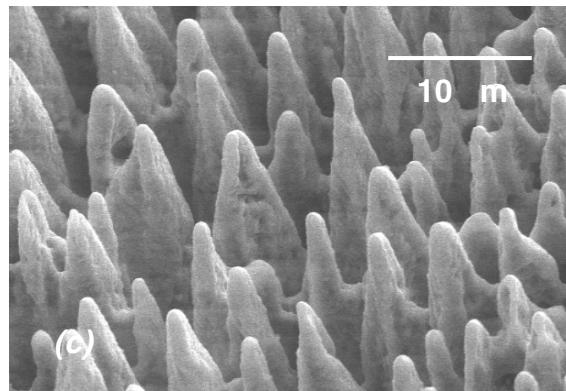
# *Microstructured silicon*



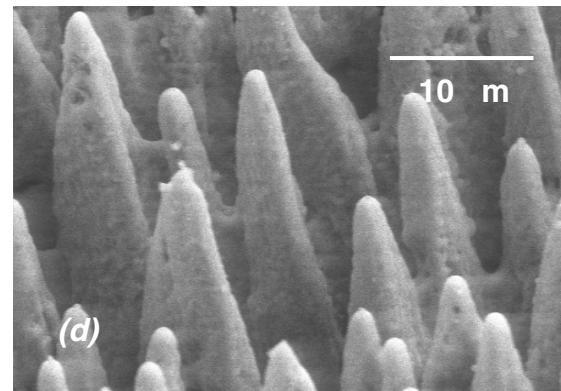
1-2  $\mu\text{m}$



4-7  $\mu\text{m}$



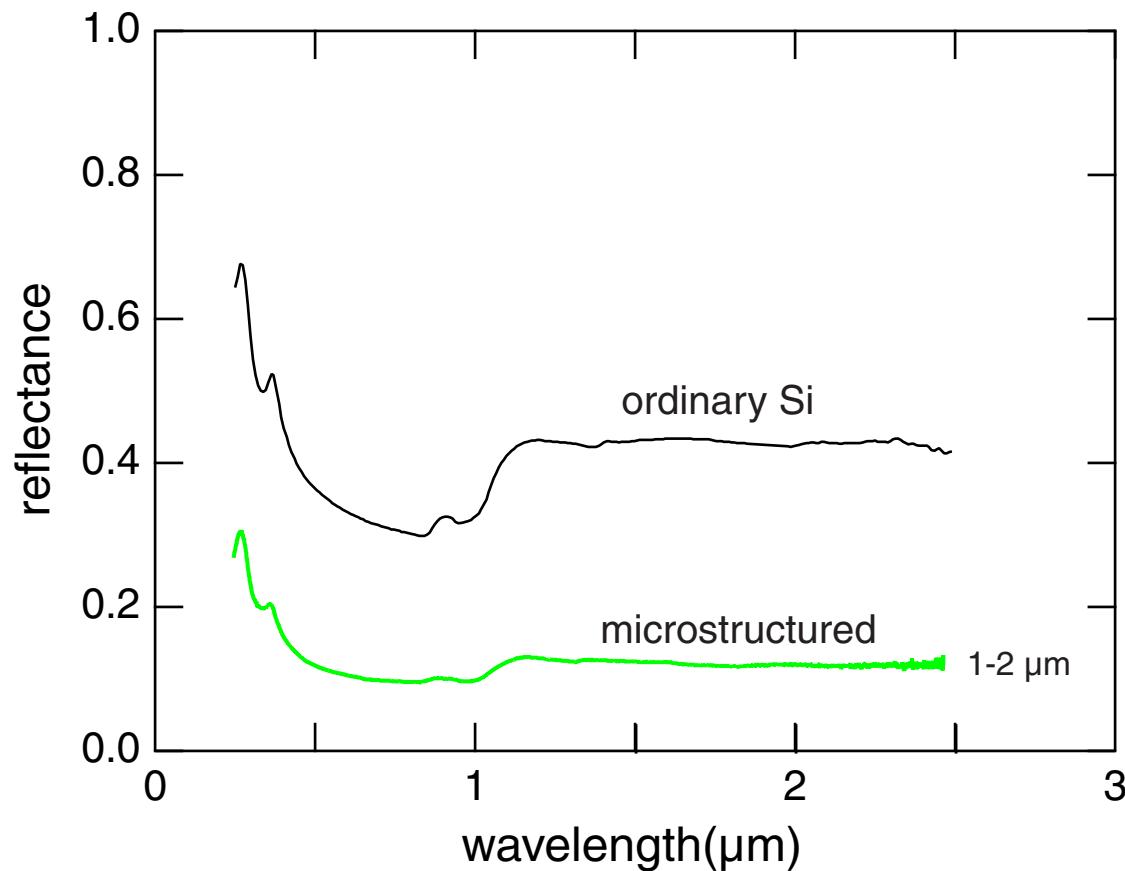
10-12  $\mu\text{m}$



18-20  $\mu\text{m}$

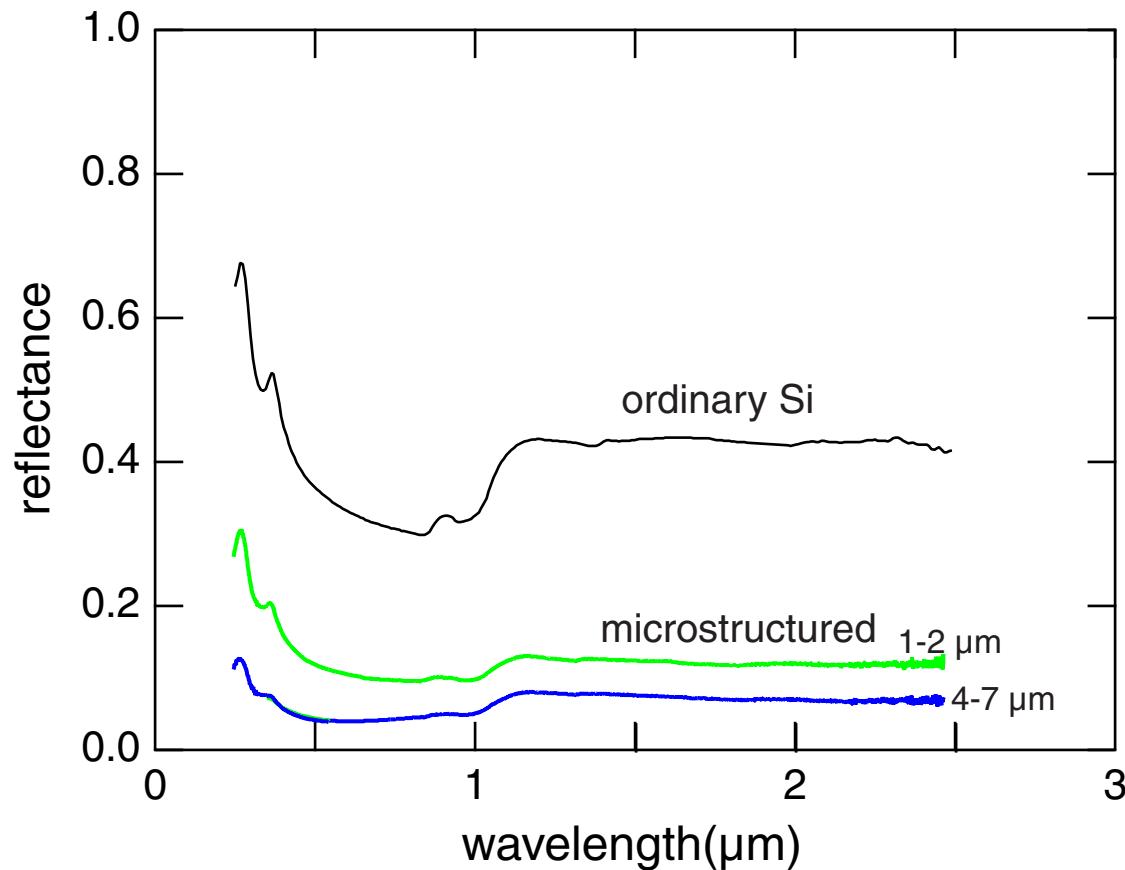
# *Microstructured silicon*

## Total integrated reflectance



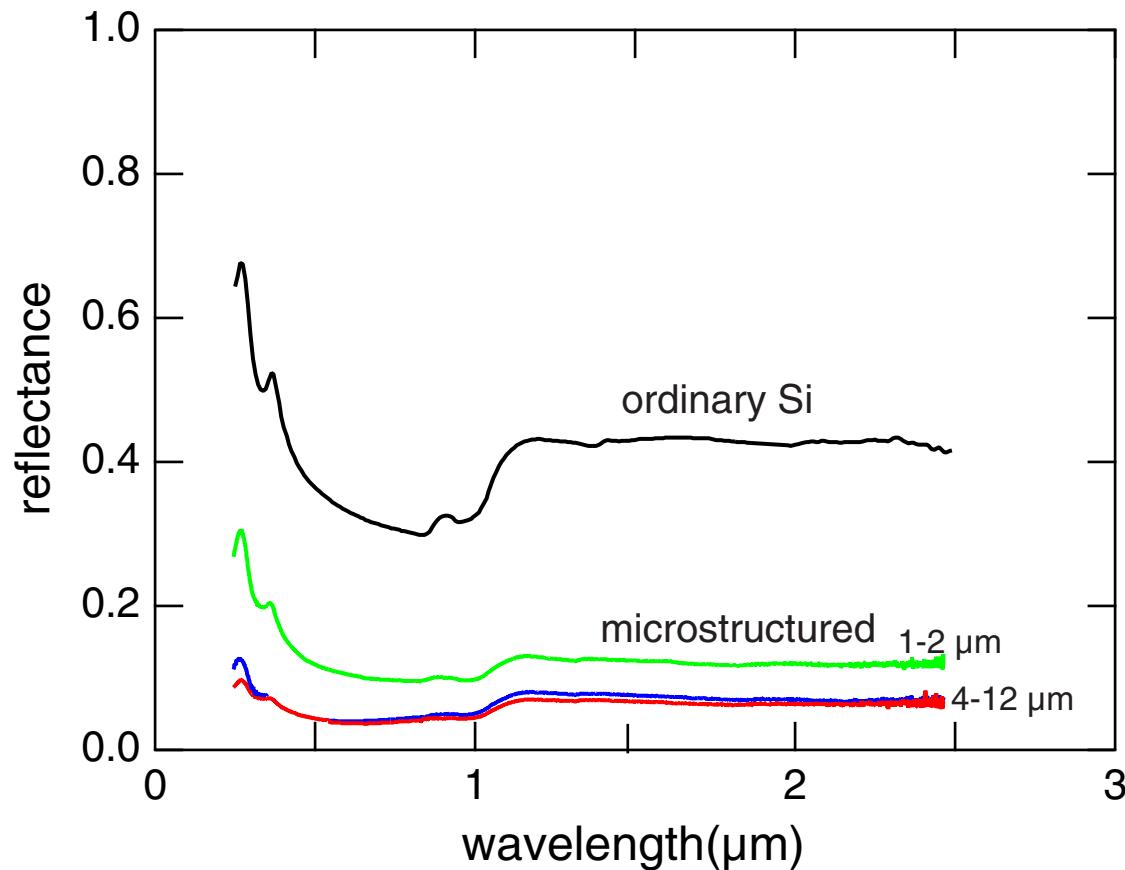
# *Microstructured silicon*

## Total integrated reflectance



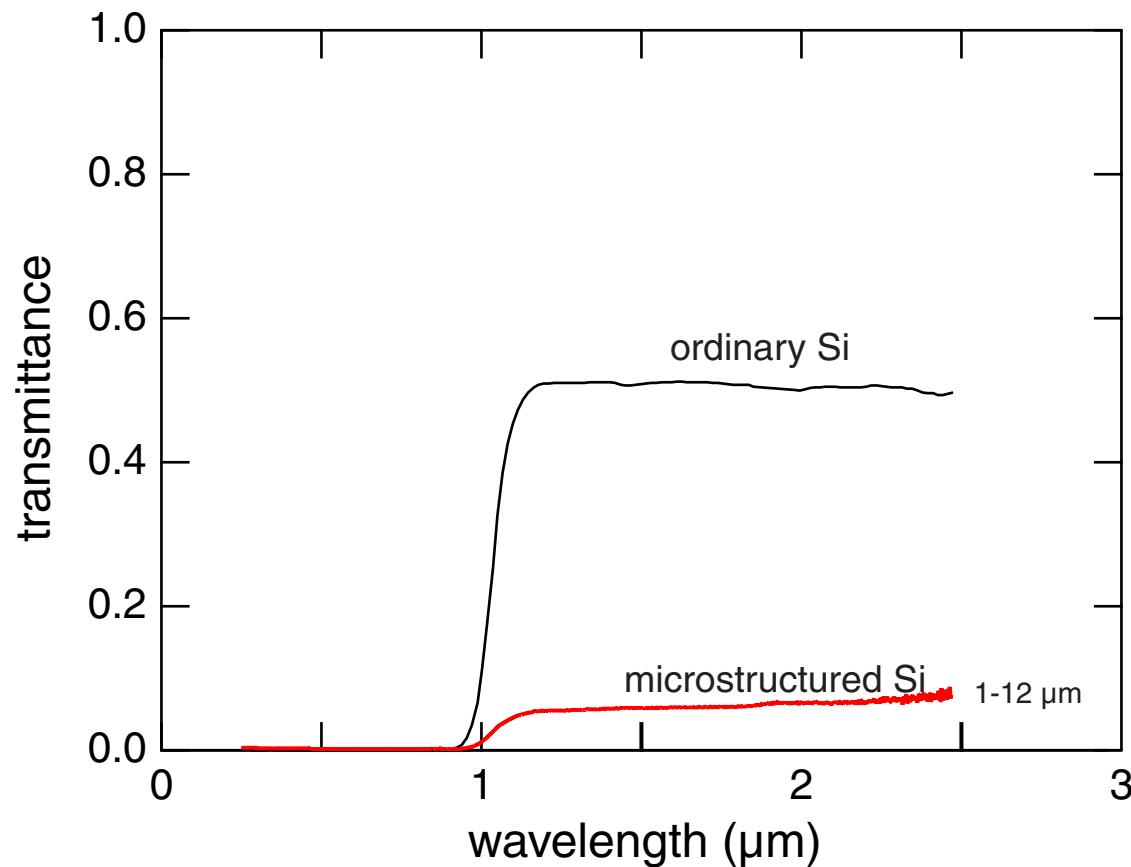
# *Microstructured silicon*

## Total integrated reflectance



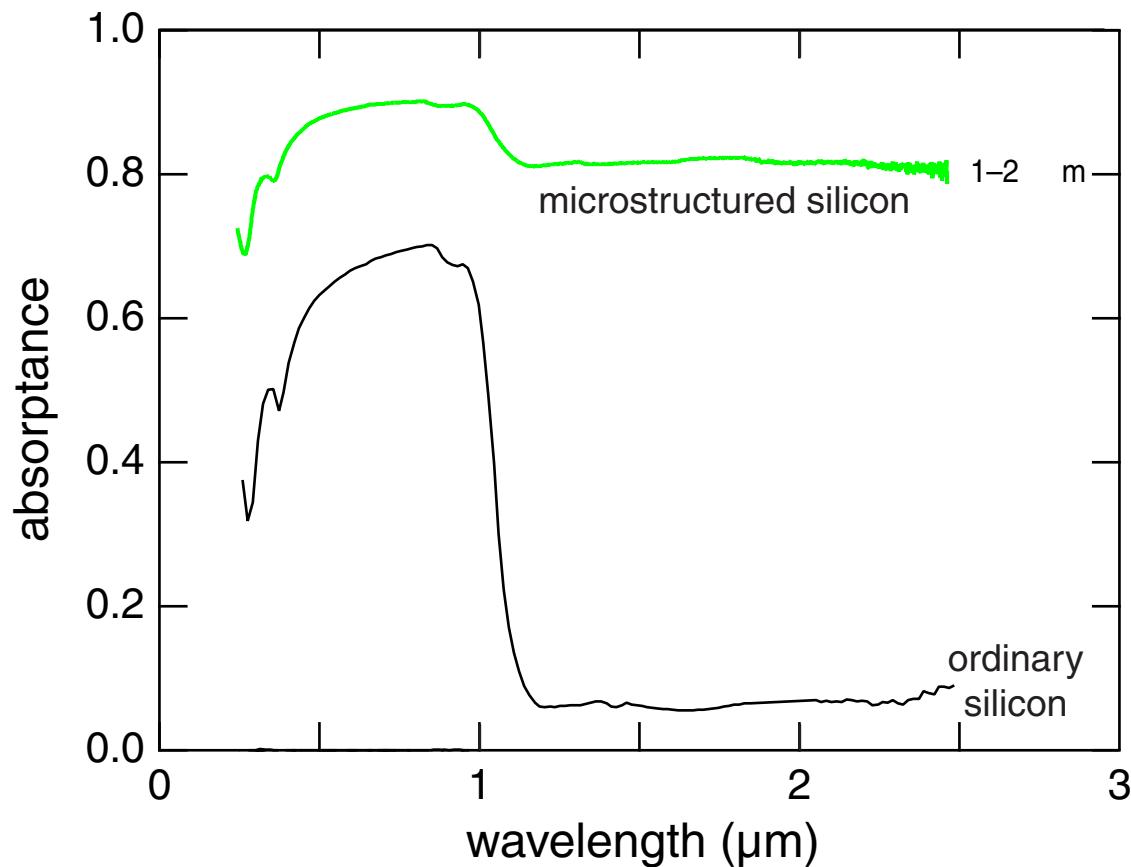
# *Microstructured silicon*

## Total integrated transmittance



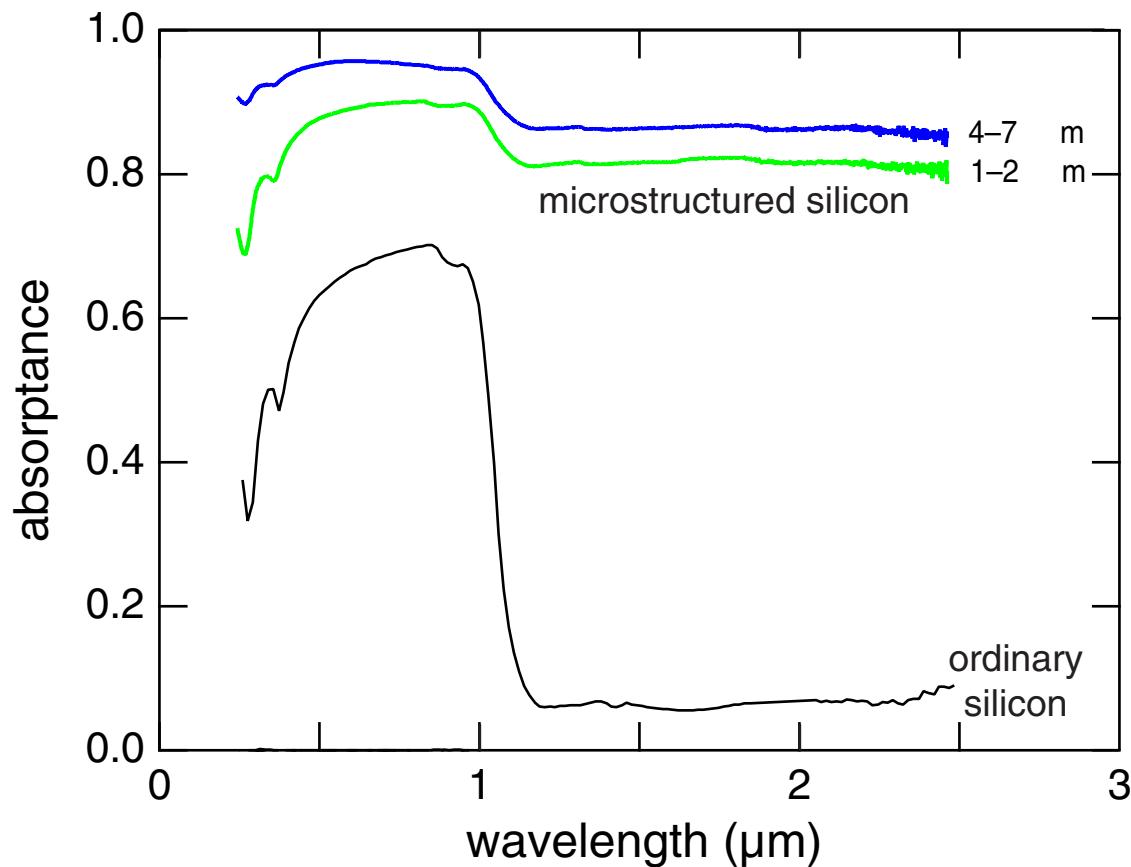
# *Microstructured silicon*

## Total absorptance



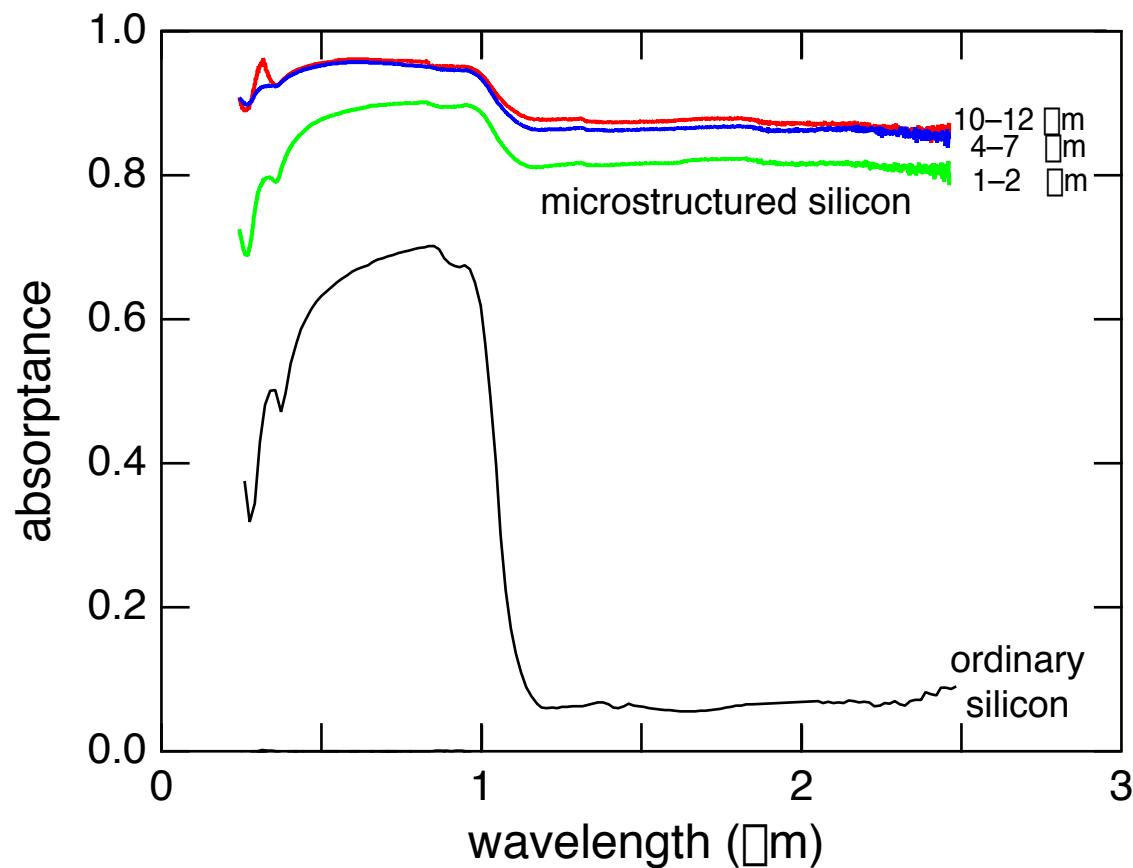
# *Microstructured silicon*

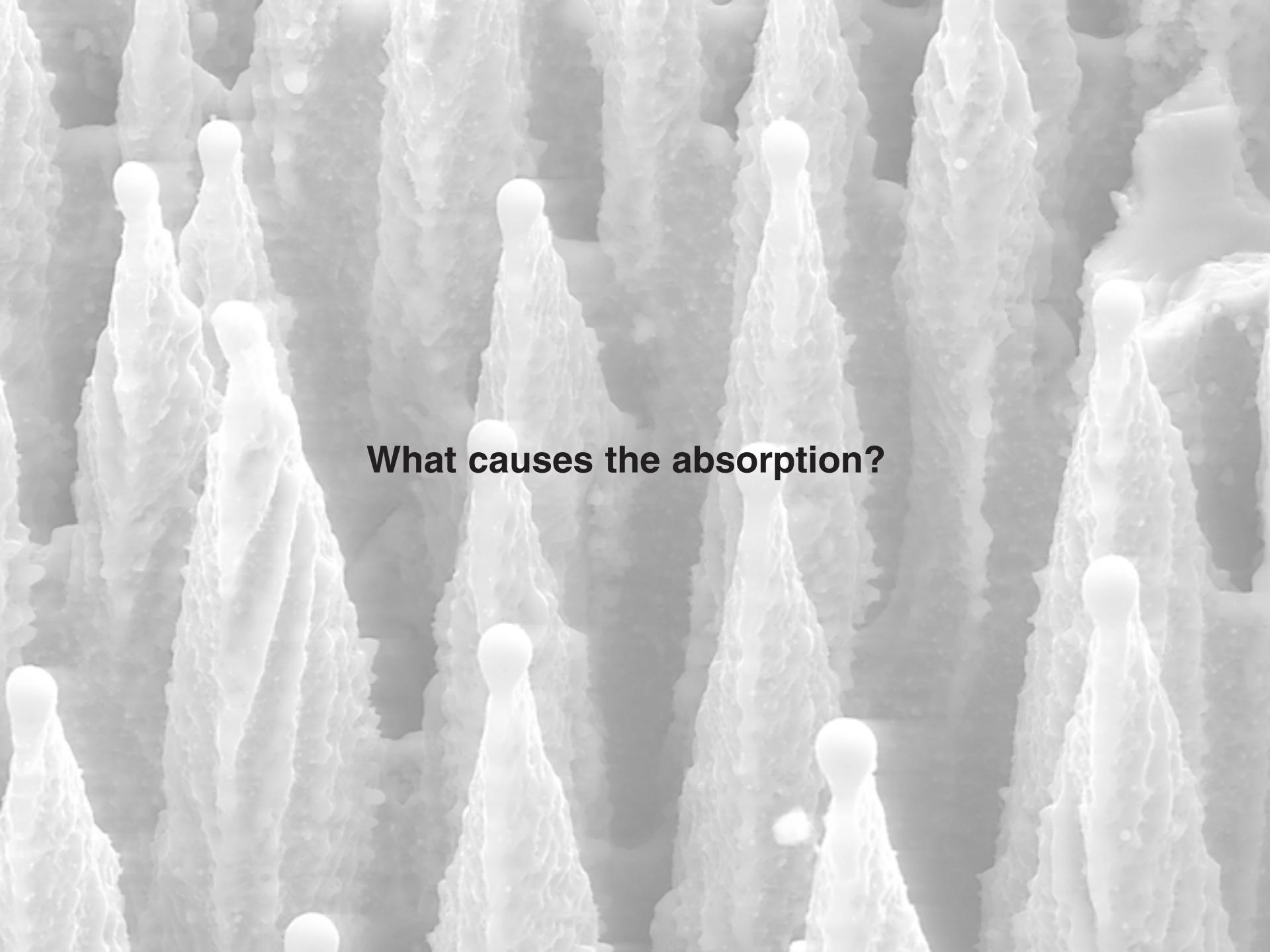
## Total absorptance



# *Microstructured silicon*

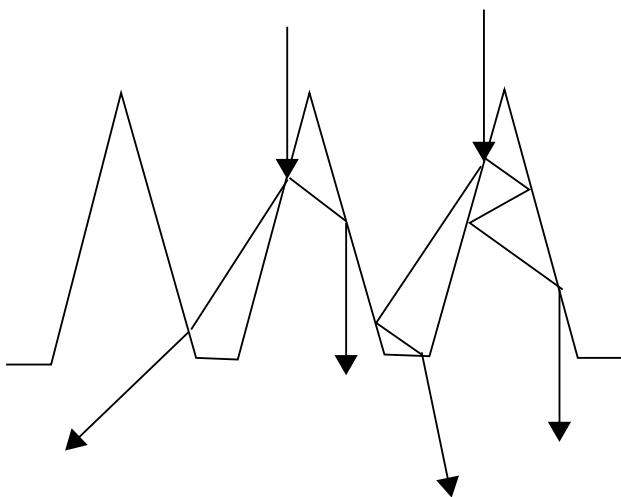
## Total absorptance



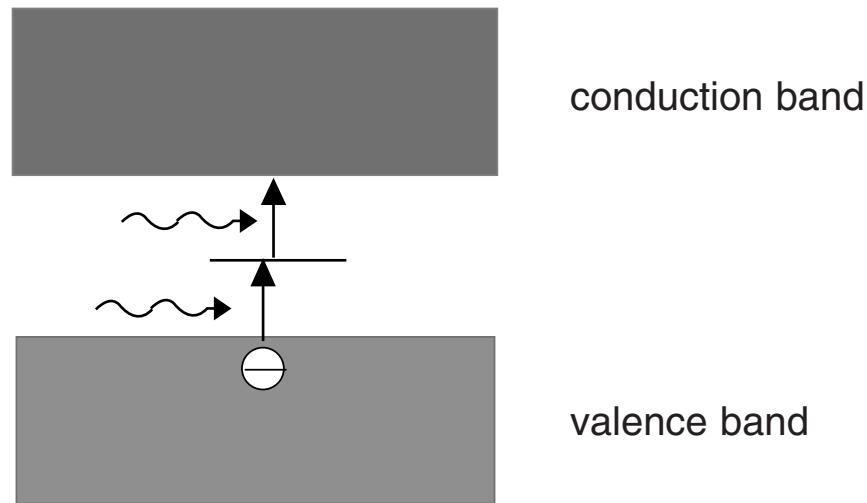


**What causes the absorption?**

## *Multiple reflections*

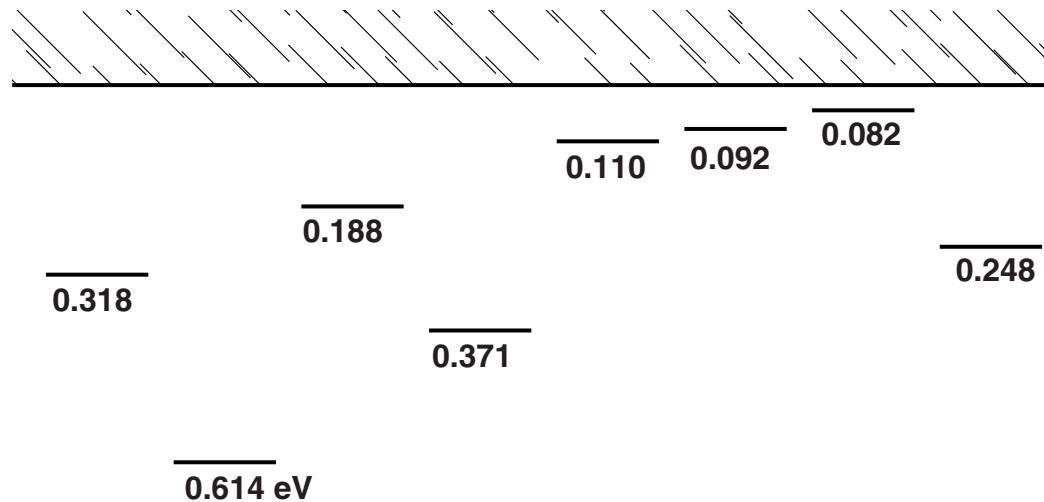


## *Below-band gap absorption*



**States in band gap allow subgap absorption**

# *Sulfur energy levels*



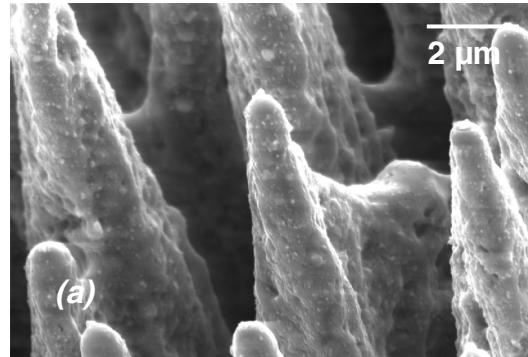
Janžen et al. Phys. Rev. B **29**, 1907 (1984)

## *Below-band gap absorption*

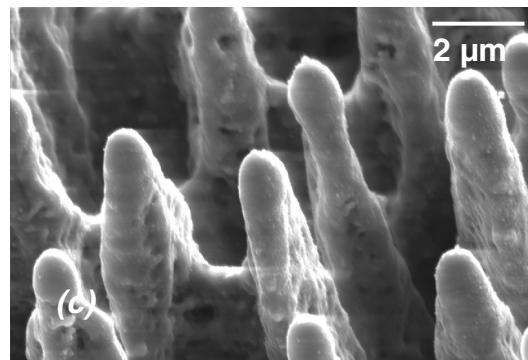
**Anneal microstructured surface  
in vacuum ( $10^{-7}$  torr) at  $910^{\circ}\text{C}$   
for 3 hours**



# *Below-band gap absorption*



**before anneal**



**after anneal**

## *Below-band gap absorption*

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

## *Below-band gap absorption*

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

**Ion channeling: structural defects persist**

## *Below-band gap absorption*

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

**Ion channeling: structural defects persist**

**Absorptance:**

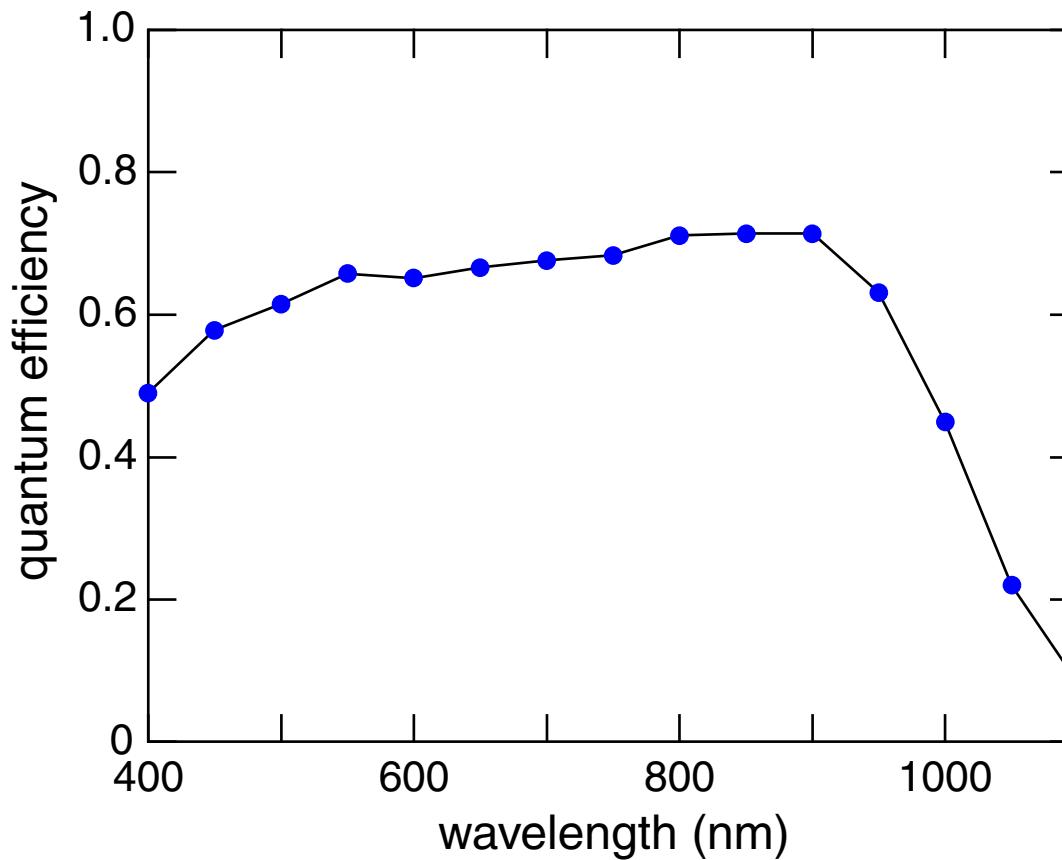
- **visible basically unchanged**
- **subgap decreases roughly twofold**

A scanning electron micrograph (SEM) showing a surface with a complex, three-dimensional texture. The surface is covered in numerous vertical, elongated ridges of varying heights. Interspersed among these ridges are smaller, rounded protrusions that resemble stylized human figures standing on the ridges. The overall appearance is organic and somewhat abstract.

**Below-band gap photocurrent**

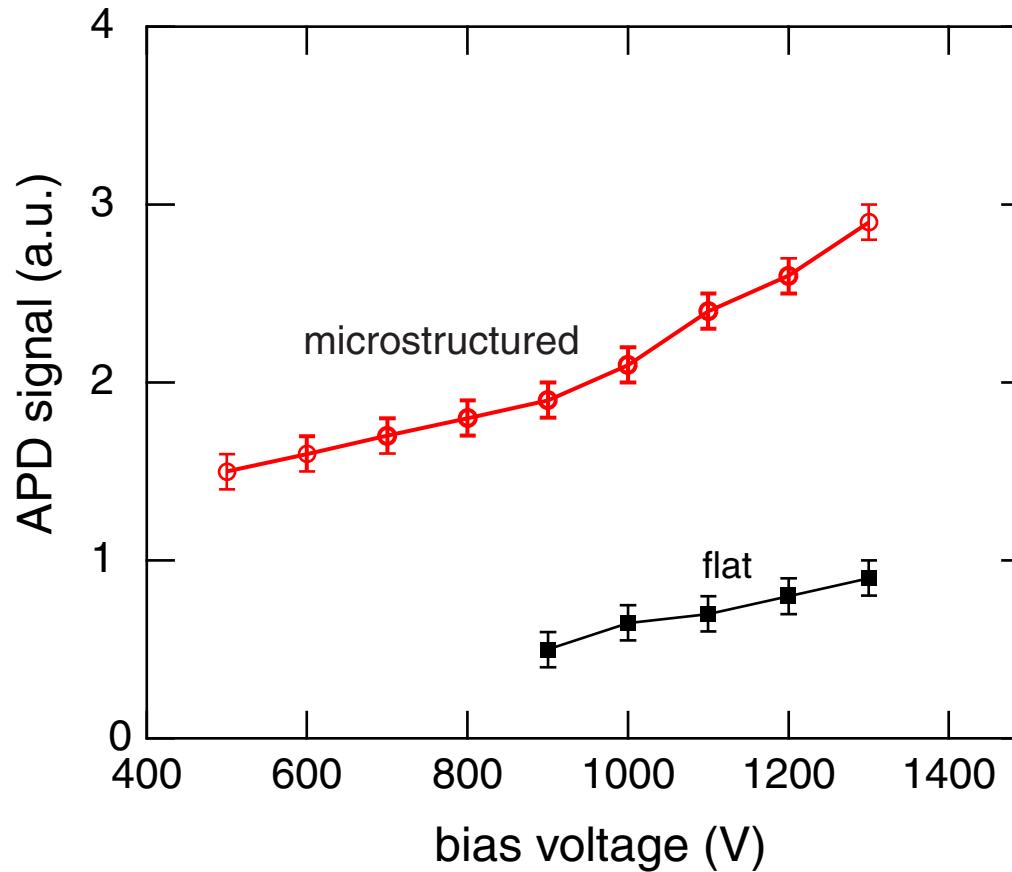
# *Below-band gap photocurrent*

## Standard silicon APD



# *Below-band gap photocurrent*

APD response at 1.3  $\mu\text{m}$



# *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  $\mu\text{m}$ , 1.33  $\mu\text{m}$

# **Acknowledgements:**

## **Collaborators:**

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

## **Assistance:**

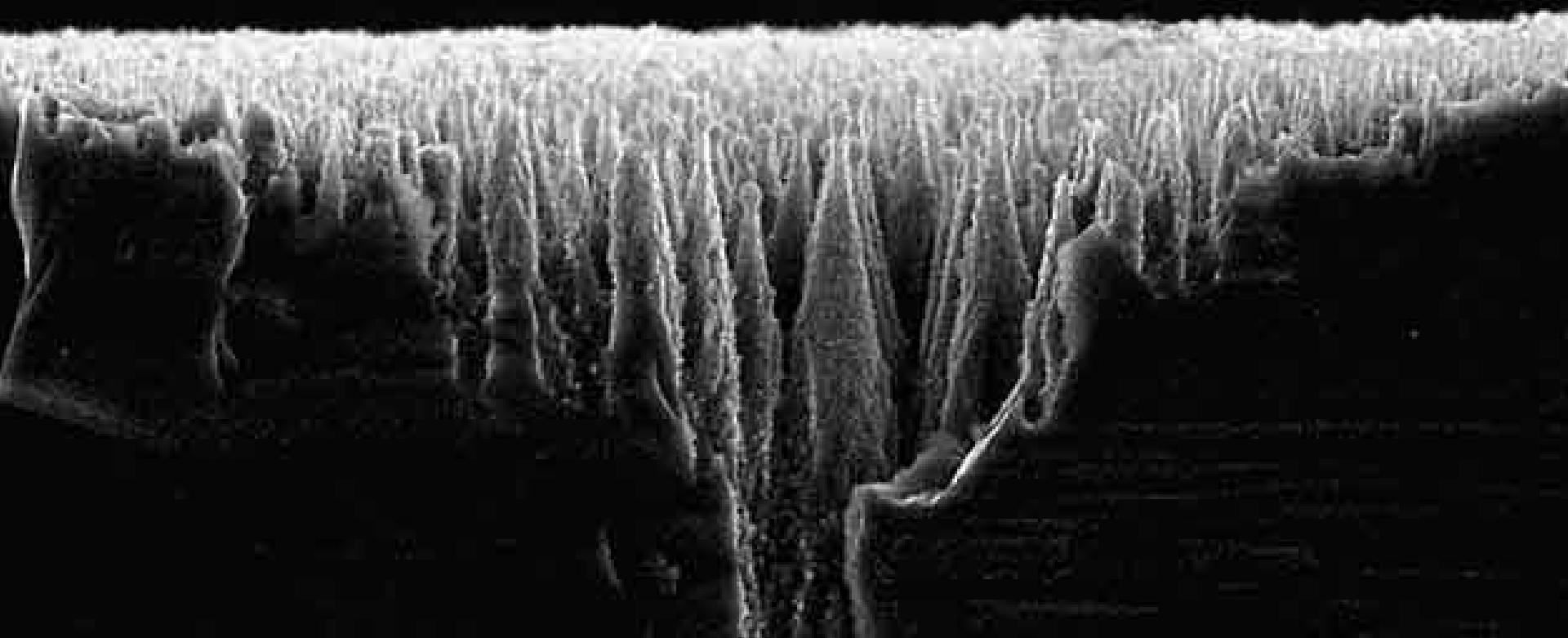
**Joseph Chen, John Chervinsky, Tom Mates, Dawen Pang**

## **Discussion:**

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

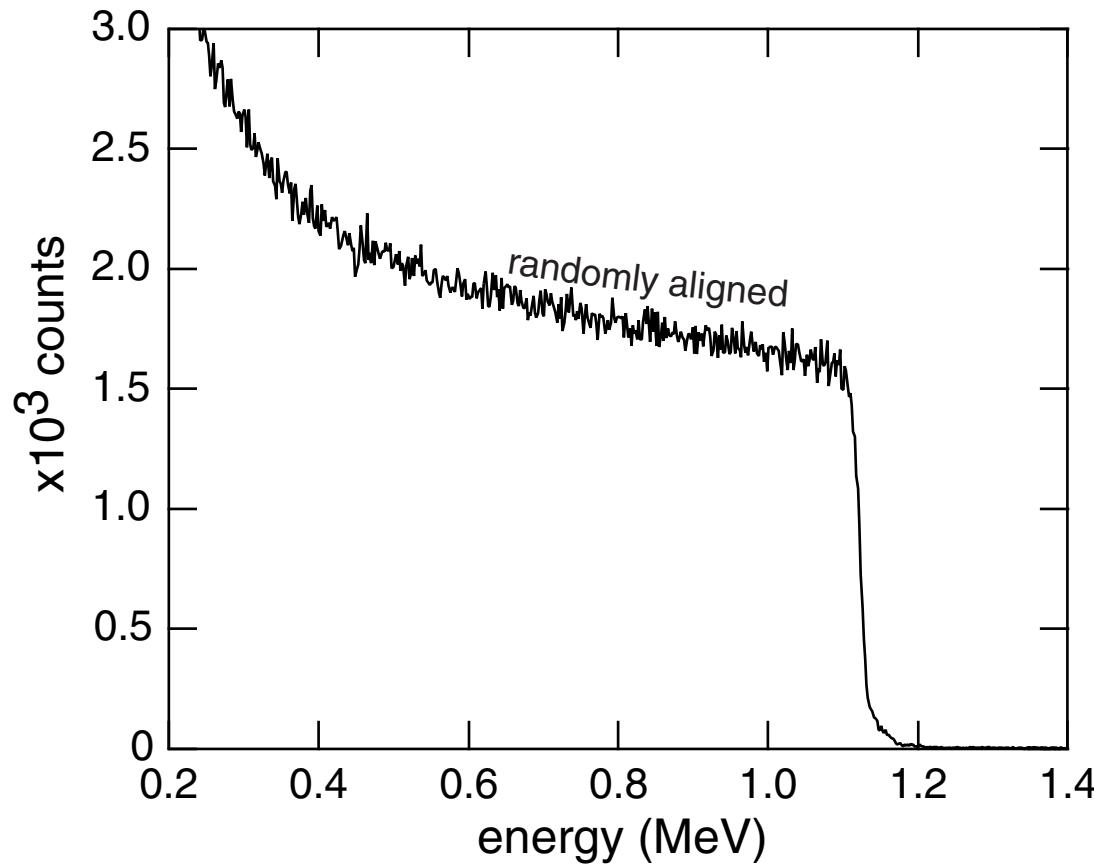
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**25 m**



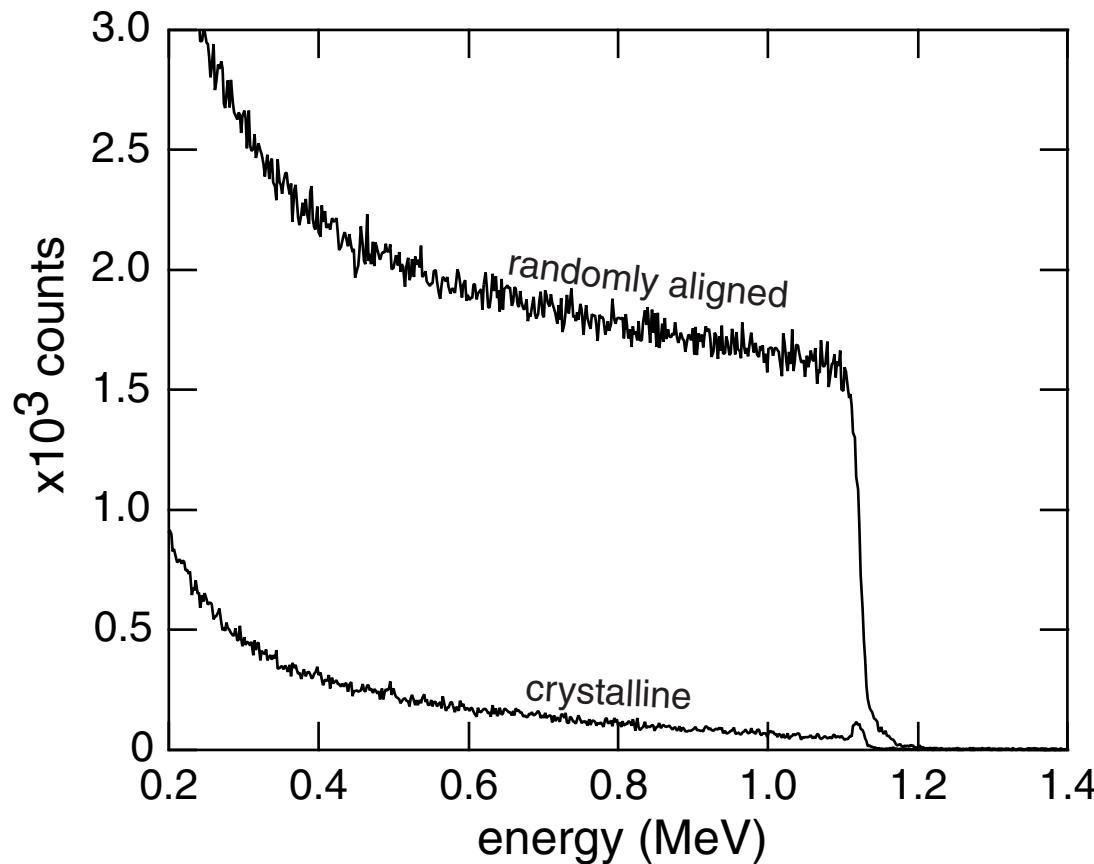
# *Structural properties*

## **Ion channeling**



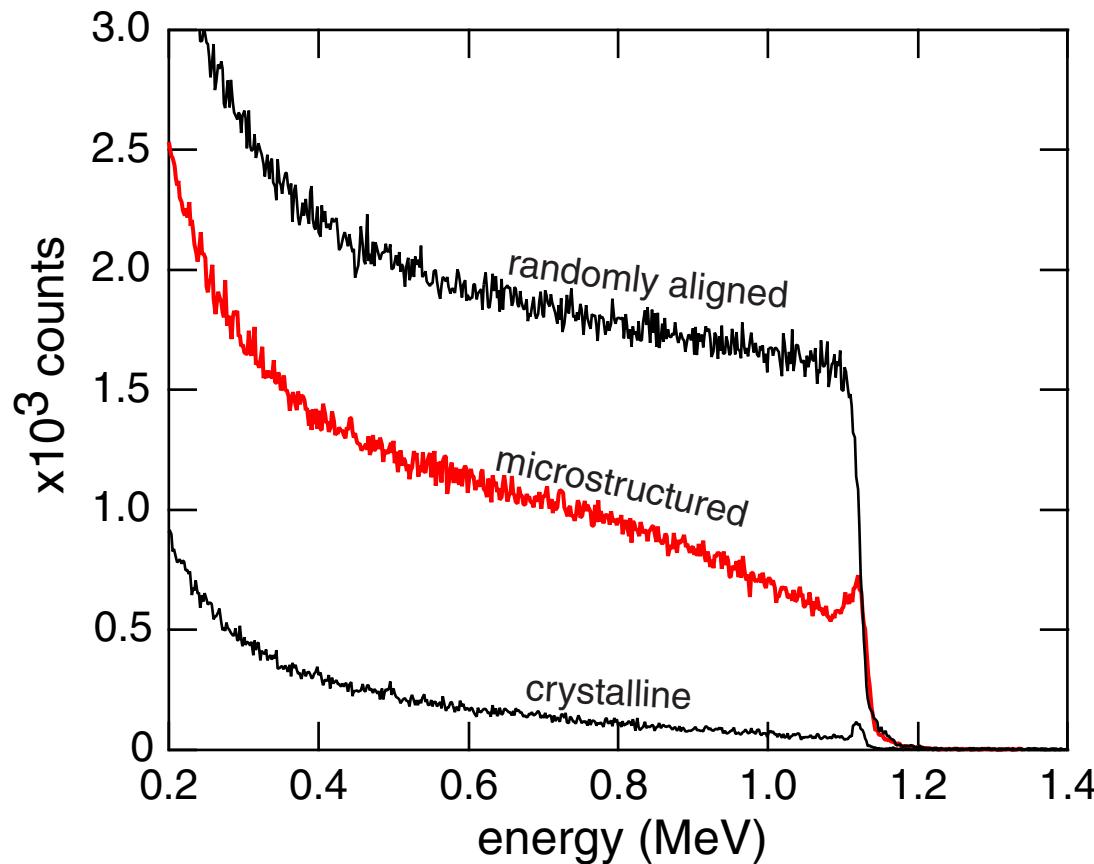
# *Structural properties*

## Ion channeling



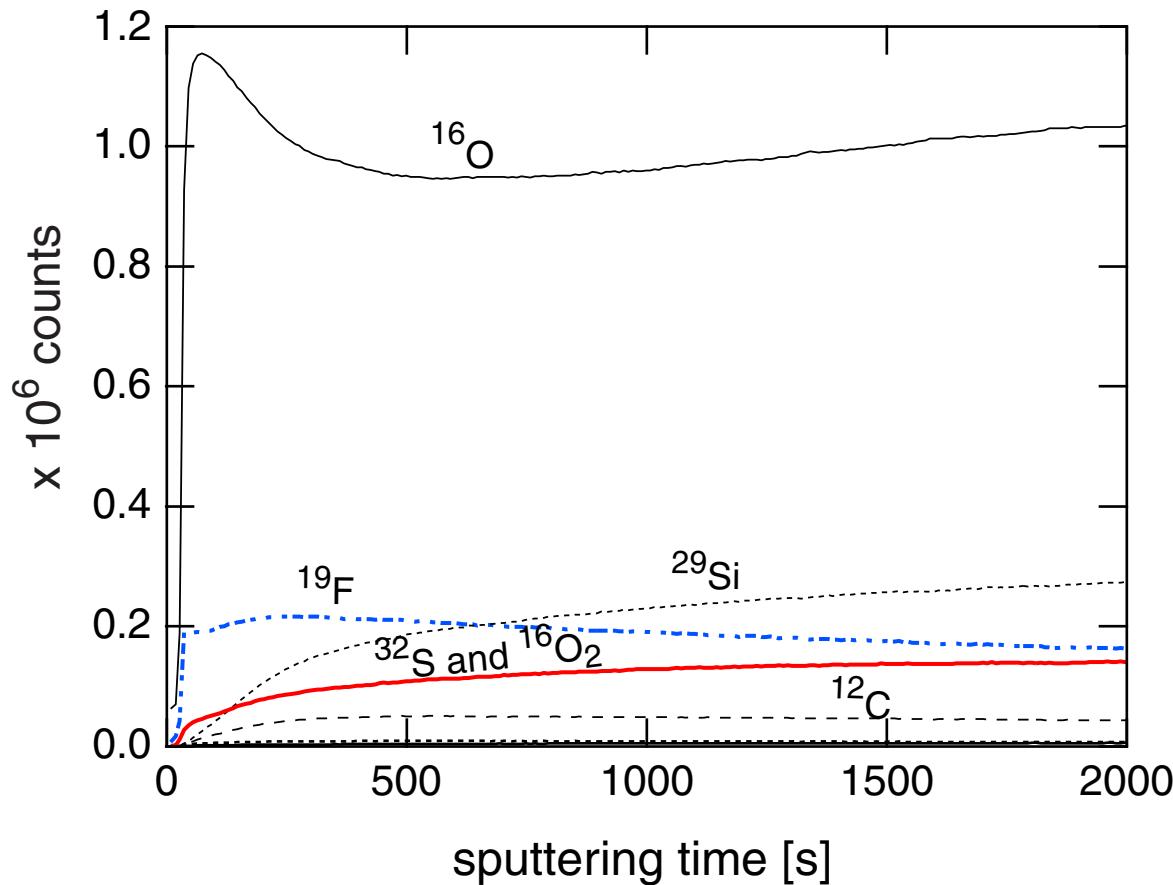
# *Structural properties*

## **Ion channeling**



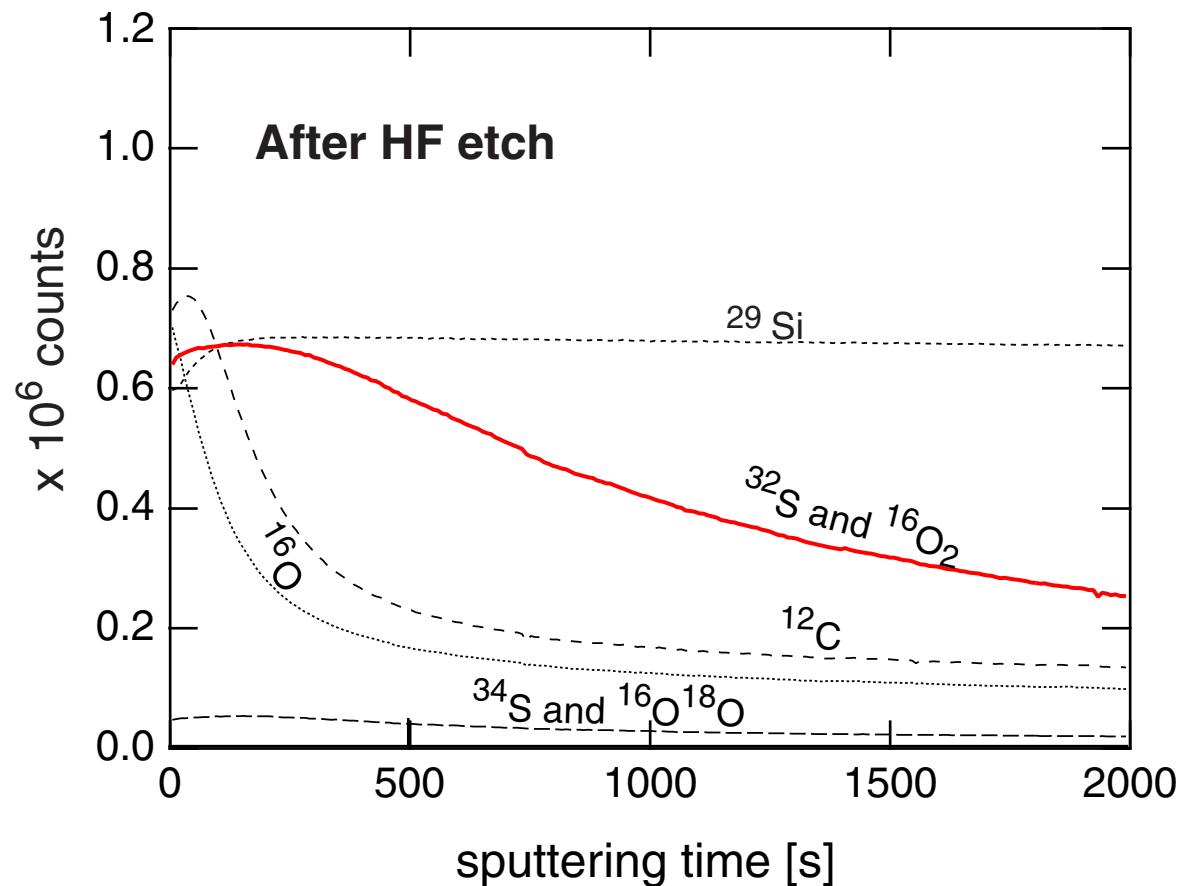
# *Chemical composition*

SIMS

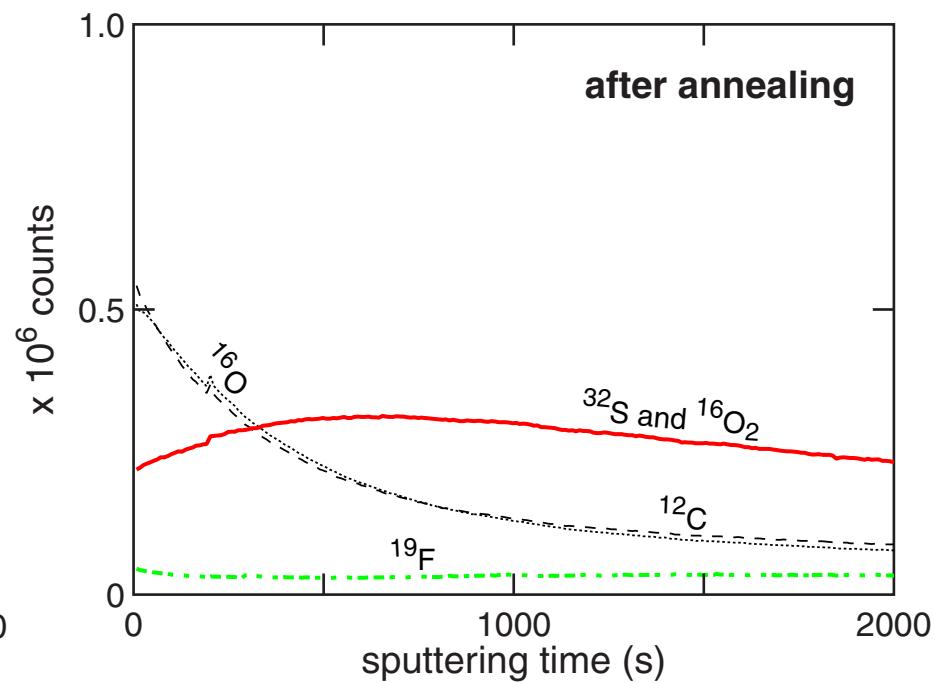
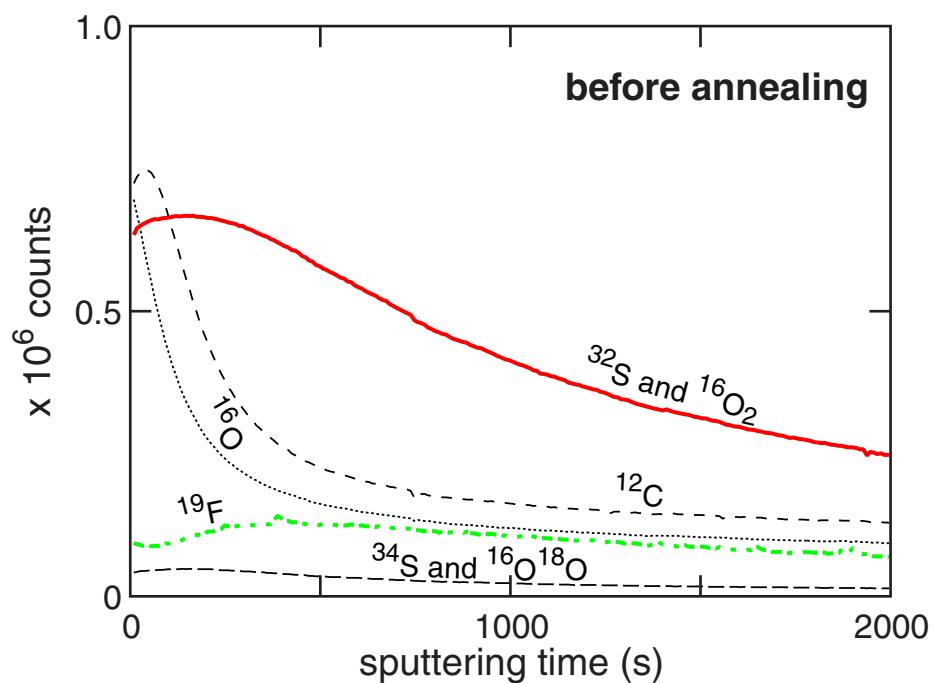


# *Chemical composition*

SIMS

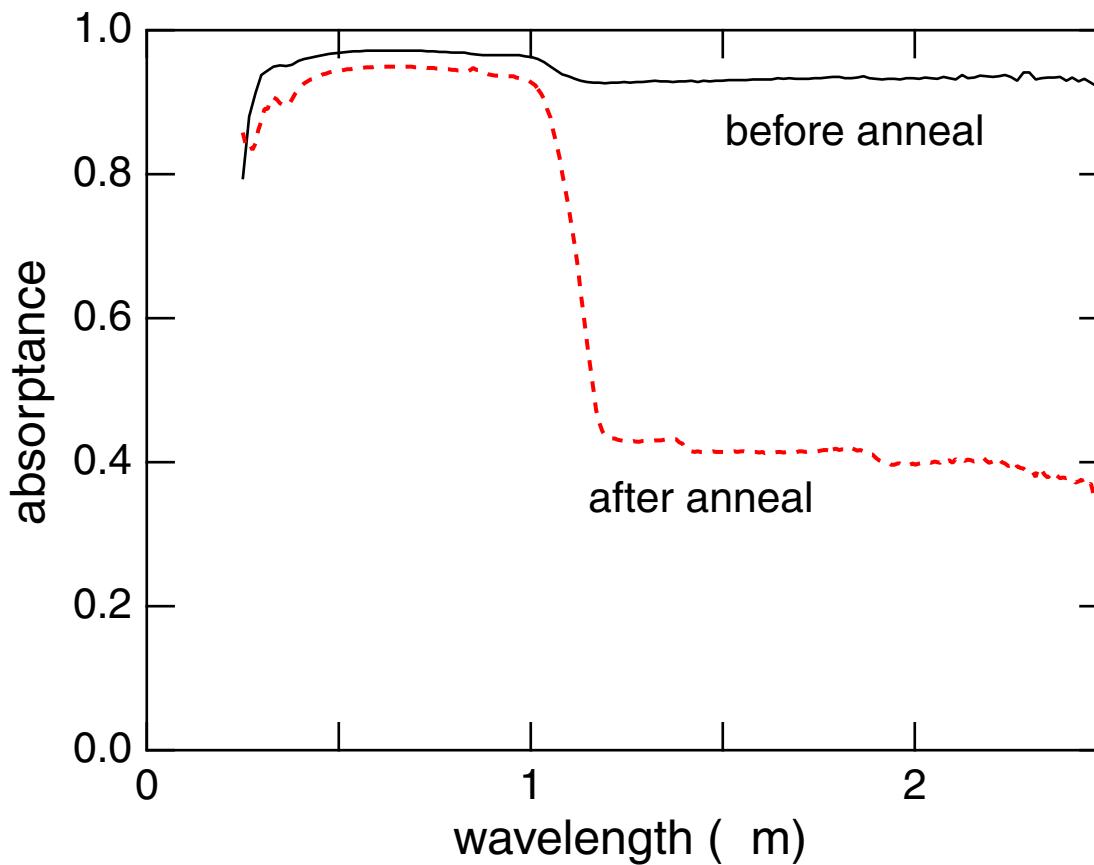


# *Below-band gap absorption*



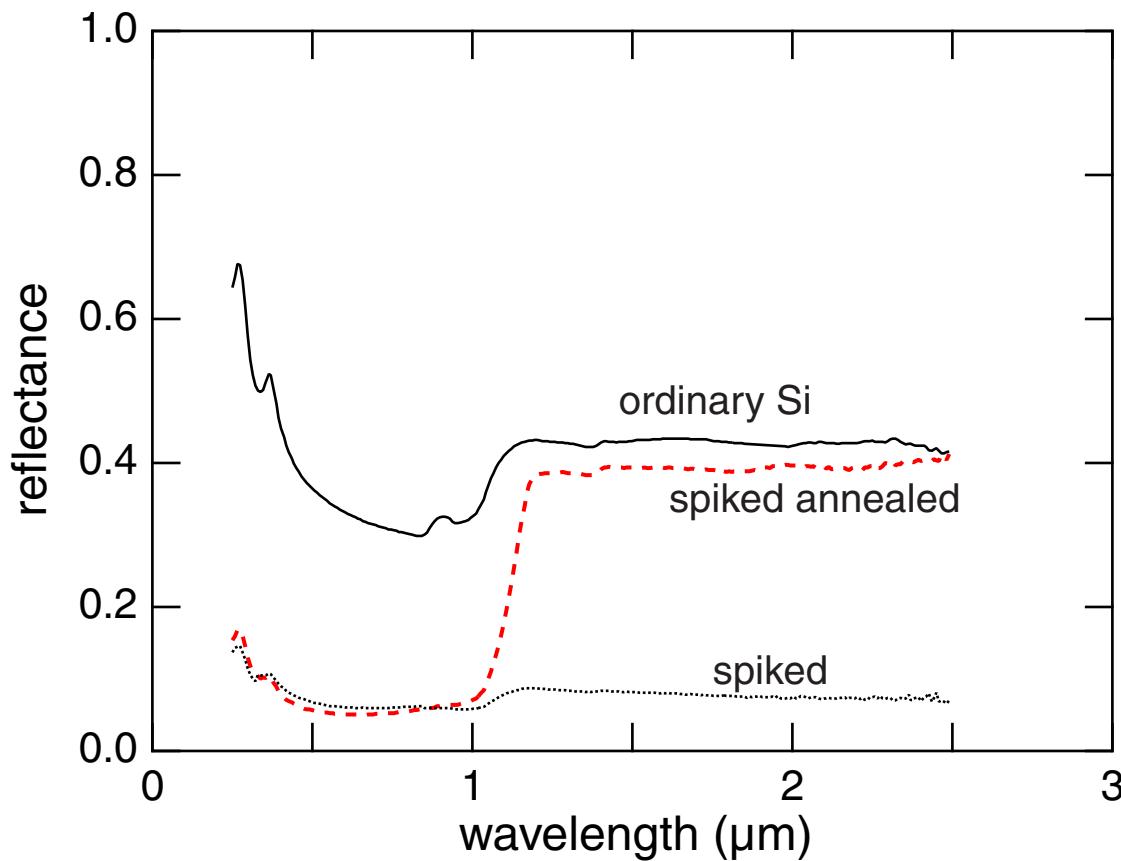
## *Below-band gap absorption*

### Total absorptance



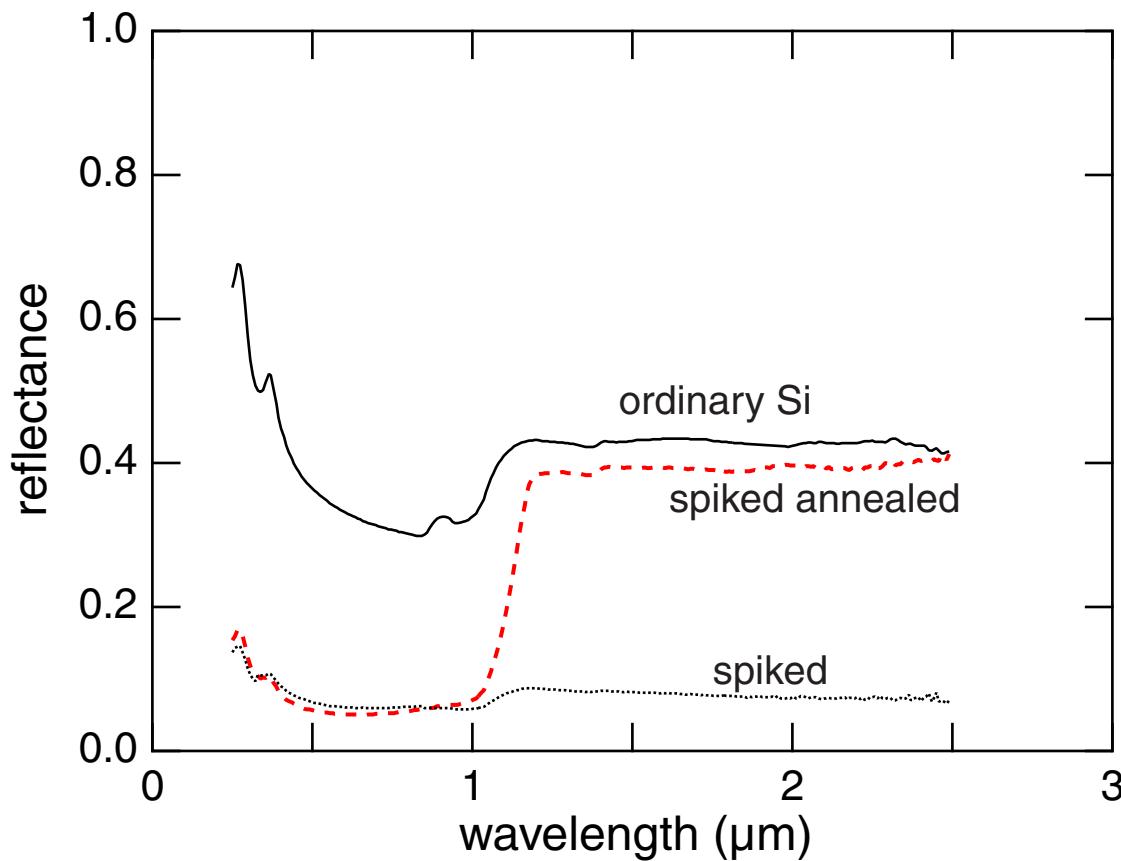
## *Below-band gap absorption*

### Total integrated reflectance



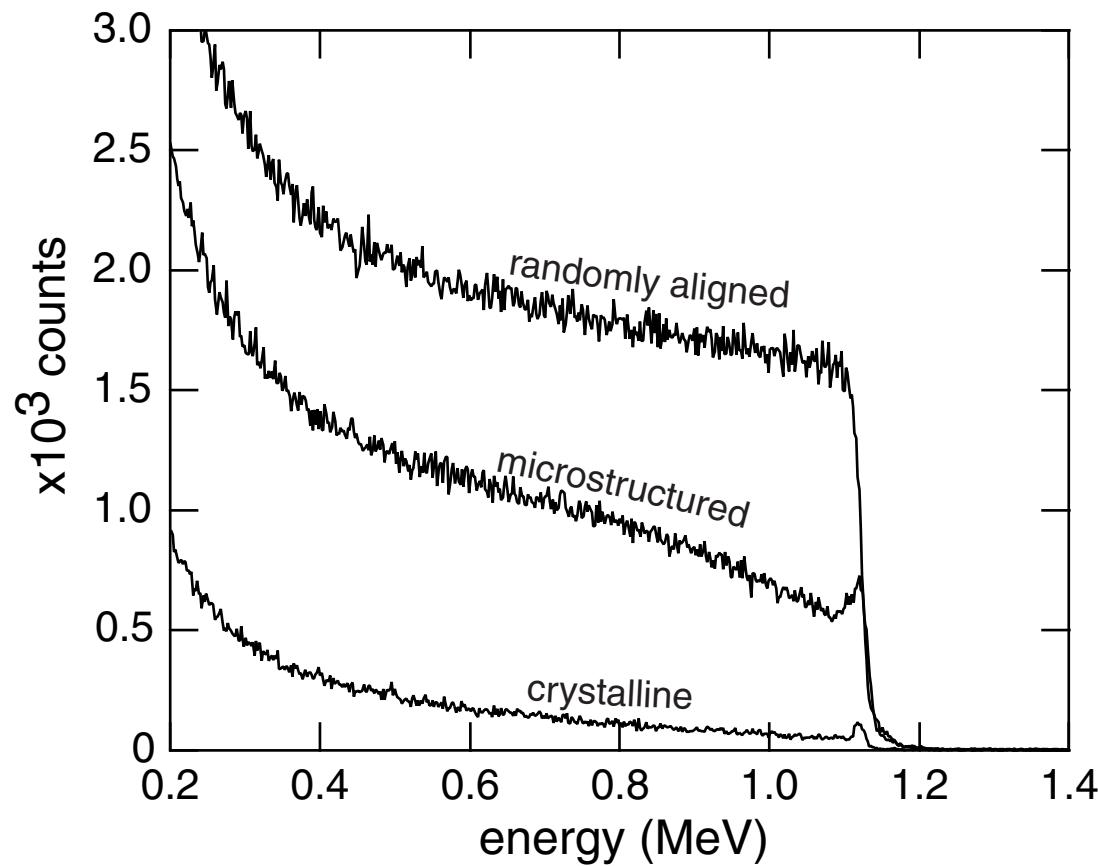
## *Below-band gap absorption*

### Total integrated reflectance



# *Below-band gap absorption*

## **Ion channeling**



# *Below-band gap absorption*

## **Ion channeling**

