Femtosecond laser-assisted microstructuring of silicon for novel detector, sensing, and display technologies

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Jim Carey
Mikey Sheehy
Catherine Crouch
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Harvard University

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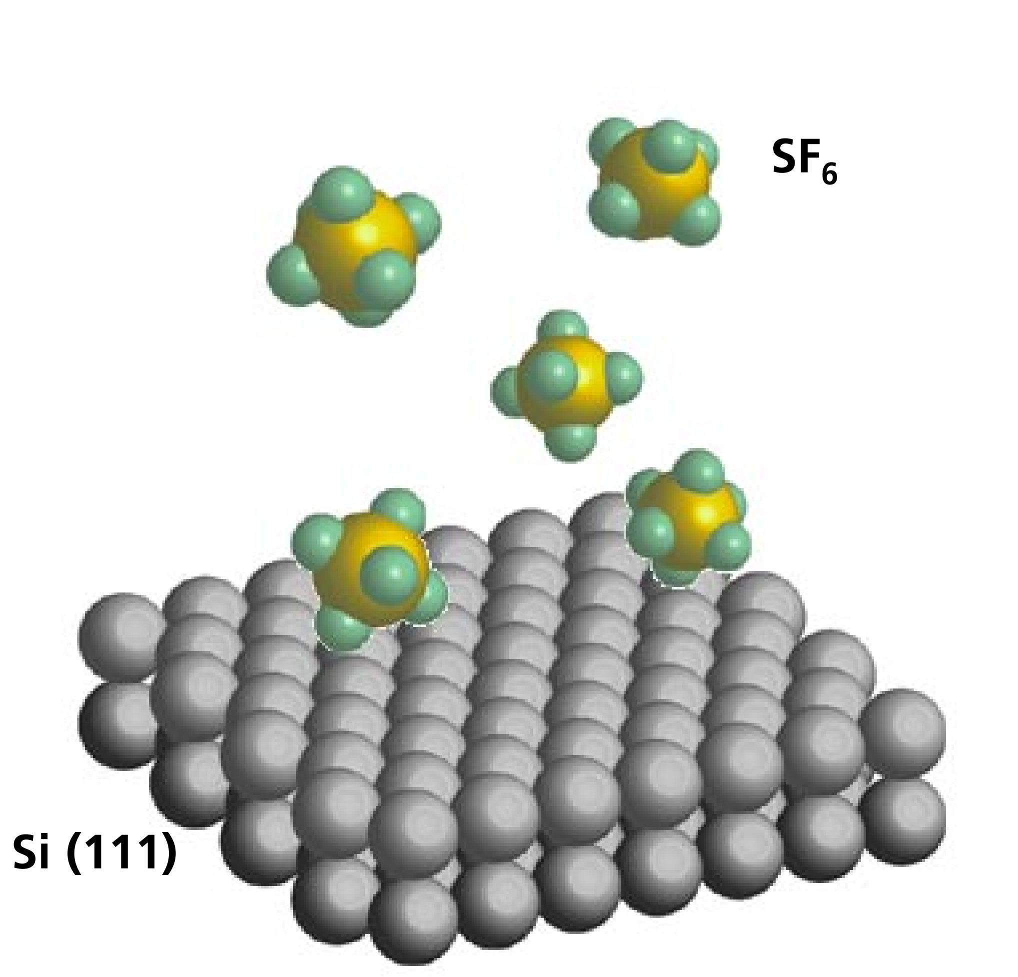
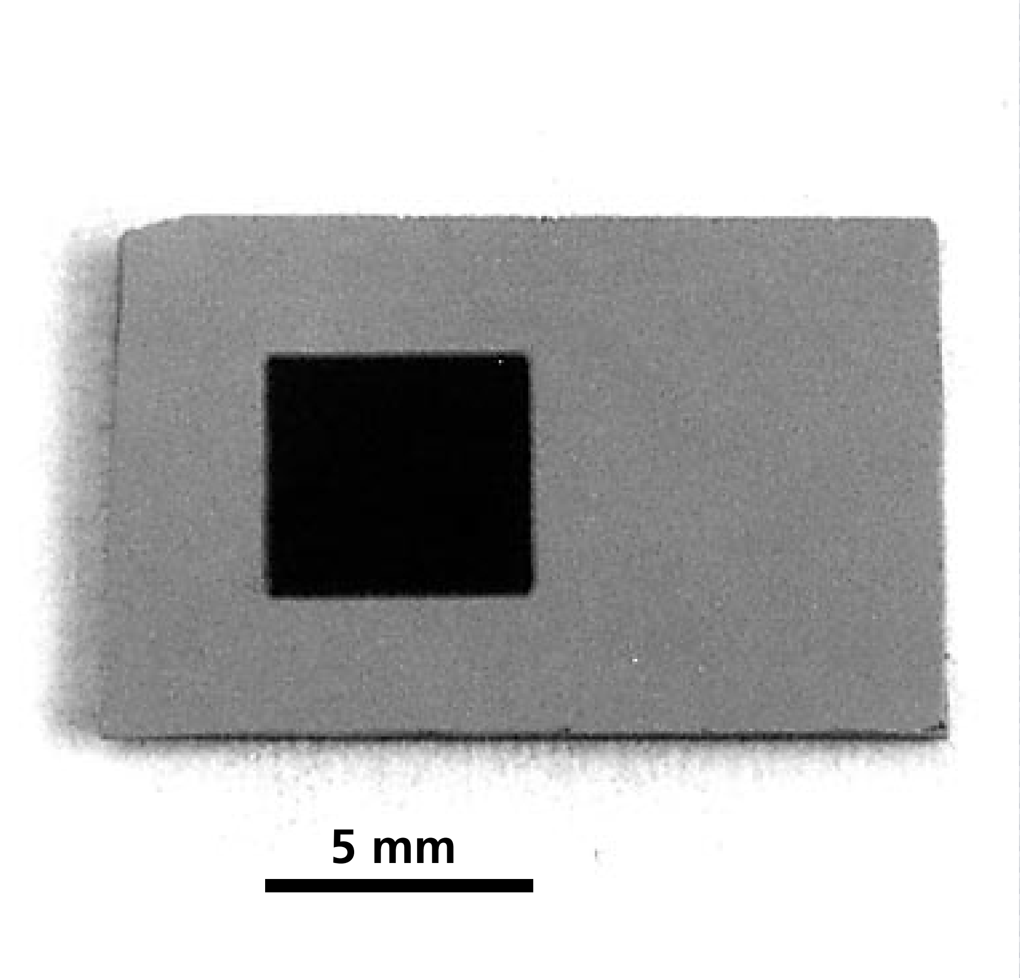
Introduction



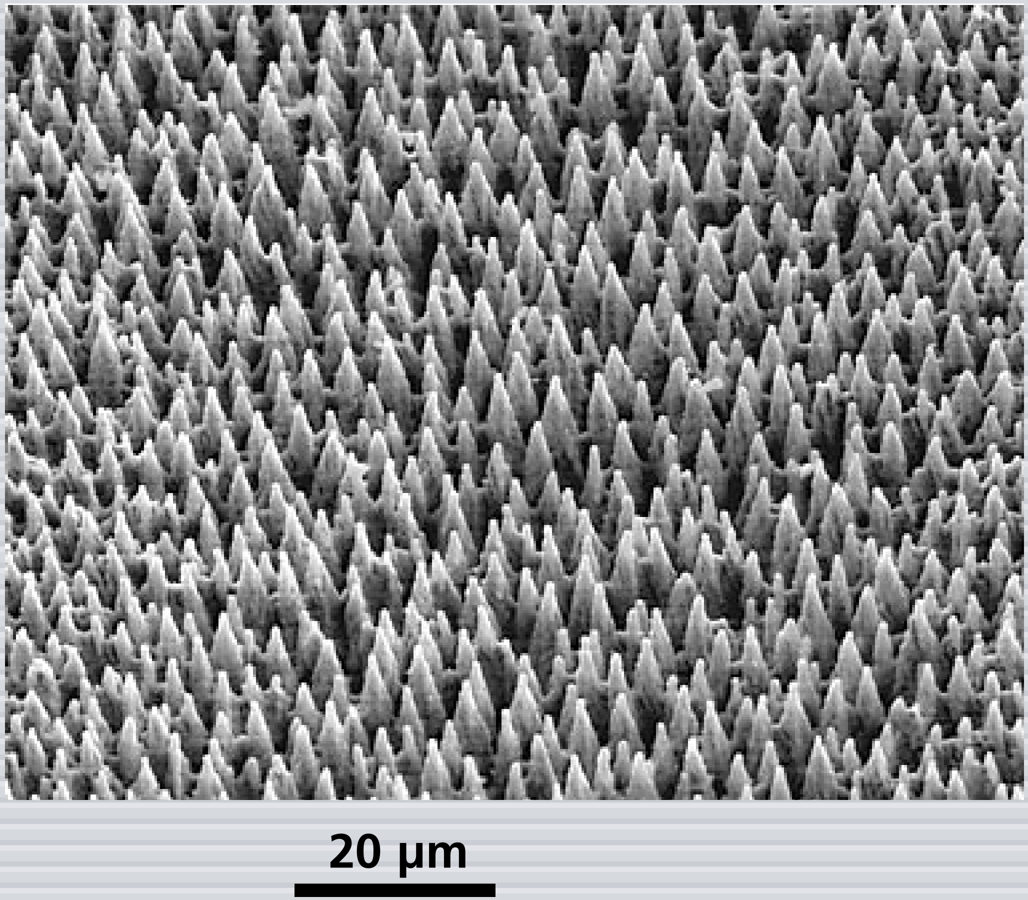
irradiate with 100-fs 10 kJ/m^2 pulses

Introduction

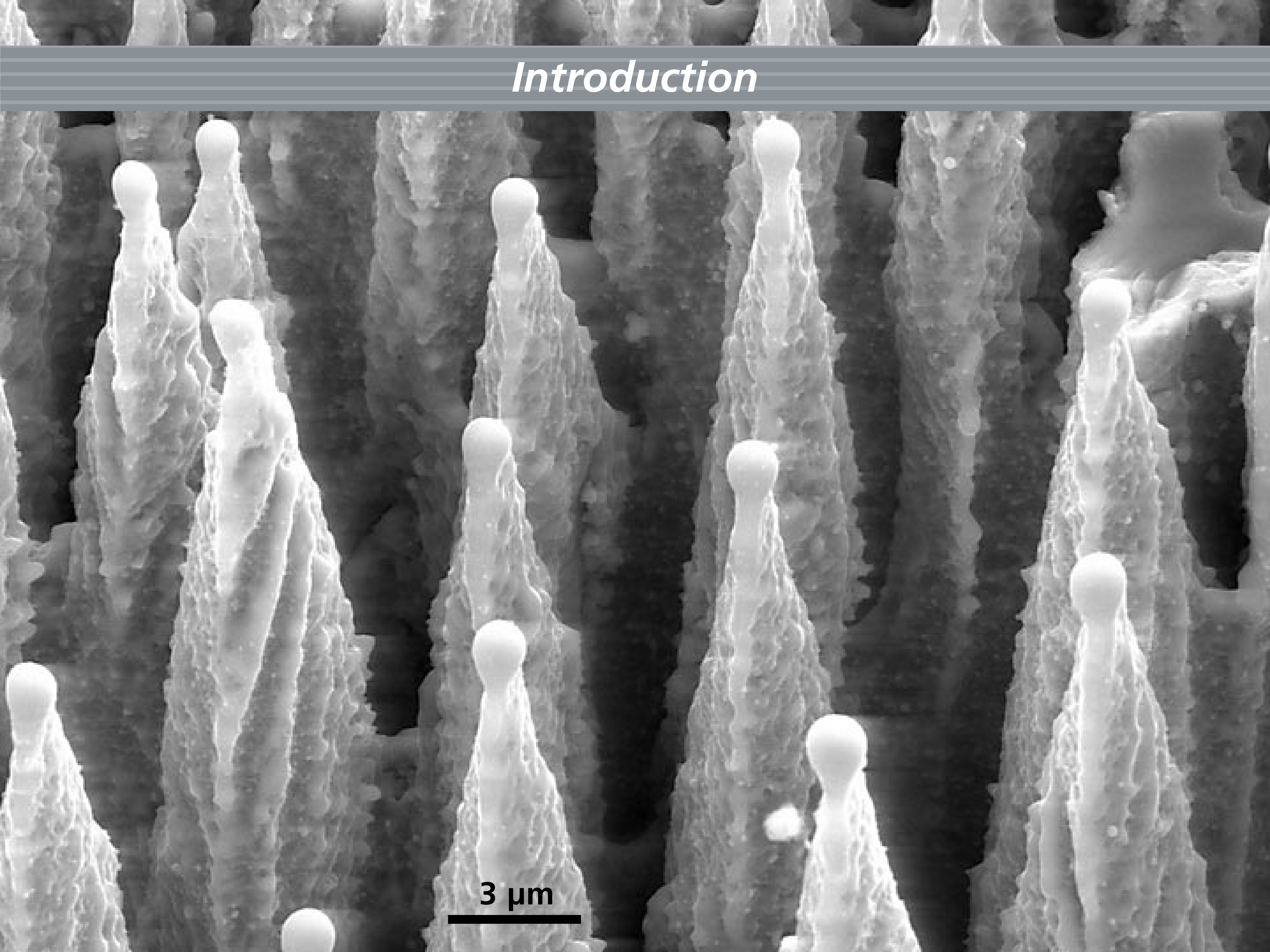


"black silicon"

Introduction



Introduction



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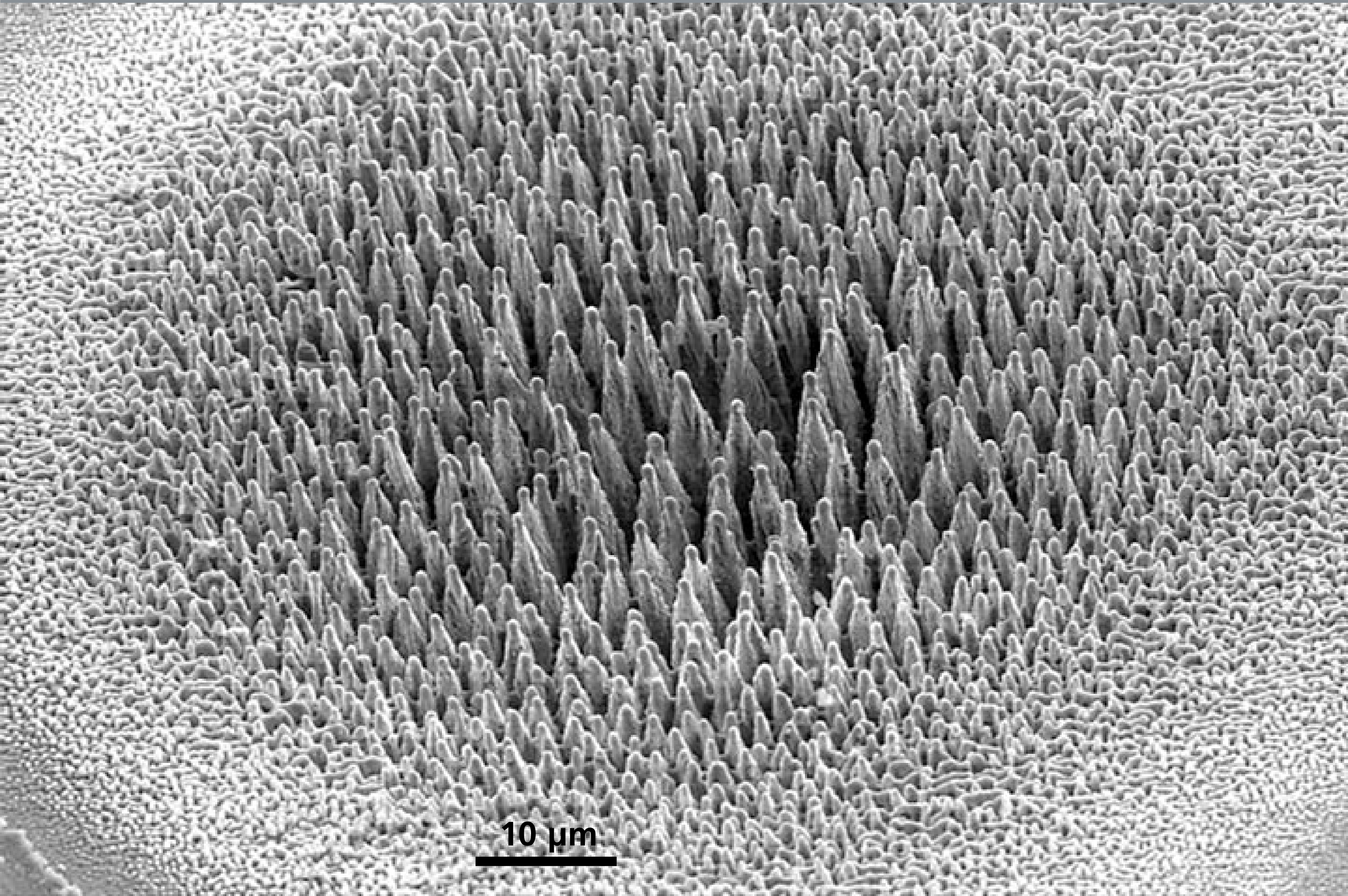
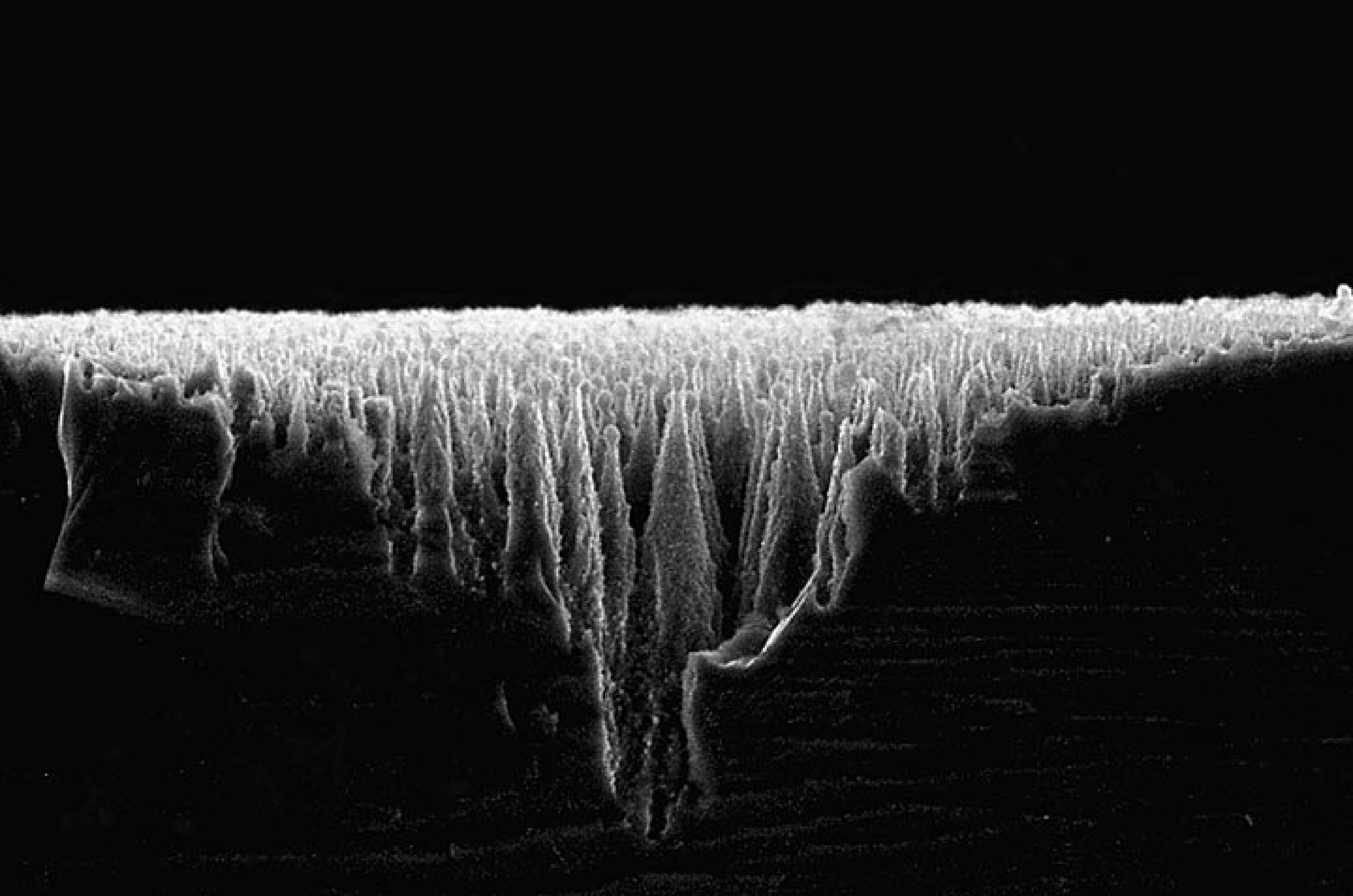


Introduction



Introduction

Introduction

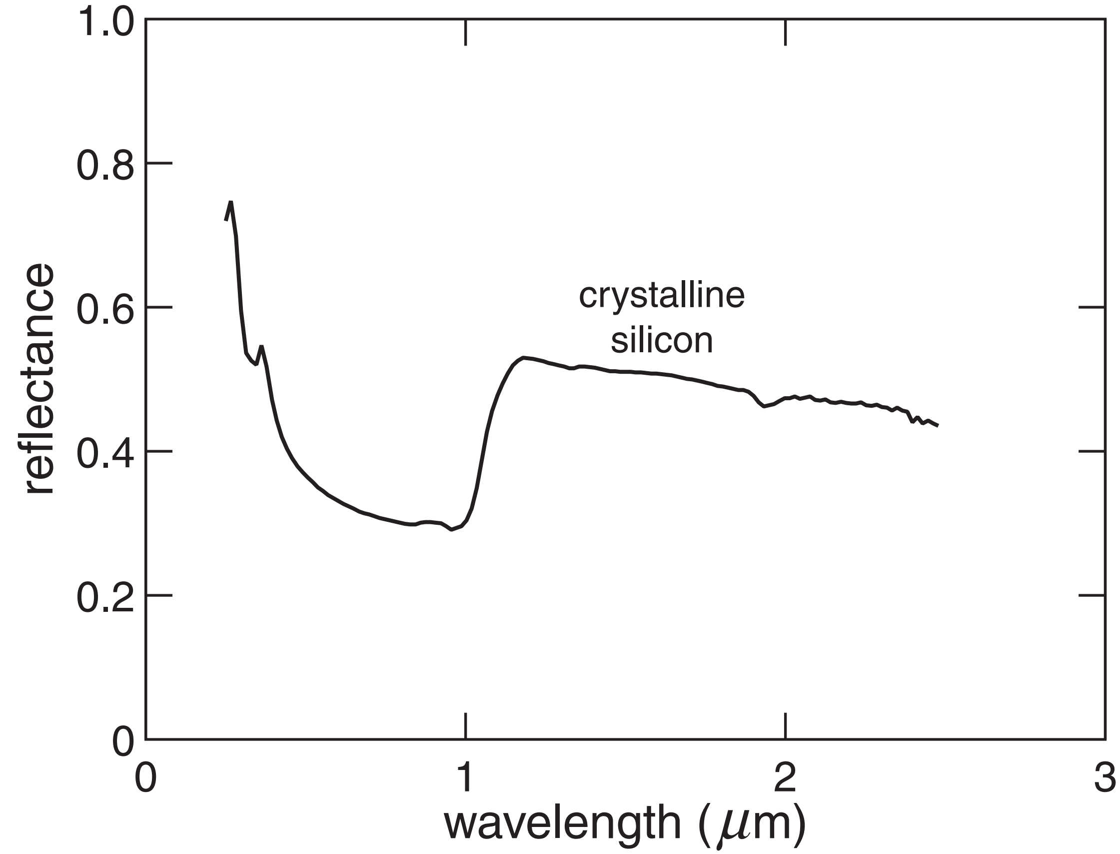
- maskless etching process
- self-organized, tall, sharp structures
- nanoscale structure on spikes

Outline

- Properties
- Structural and chemical analysis
- Outlook

Properties

reflectance (integrating sphere)



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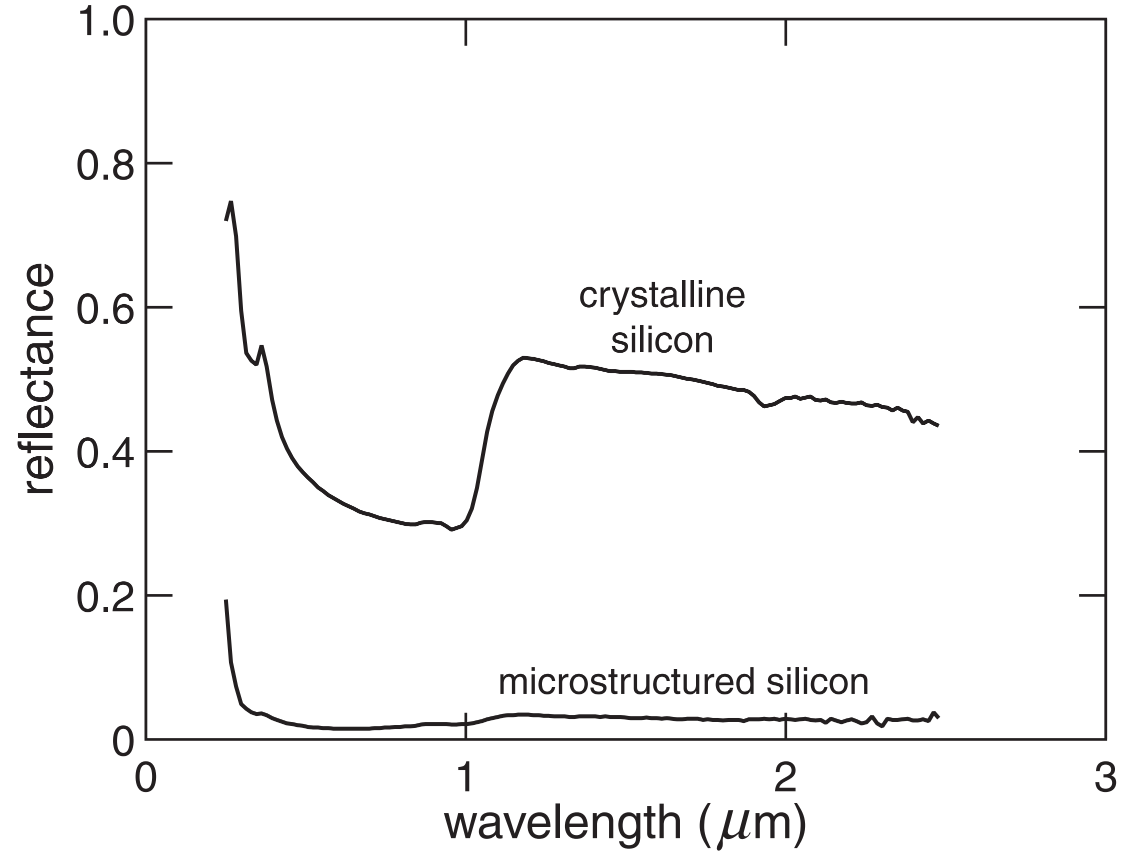
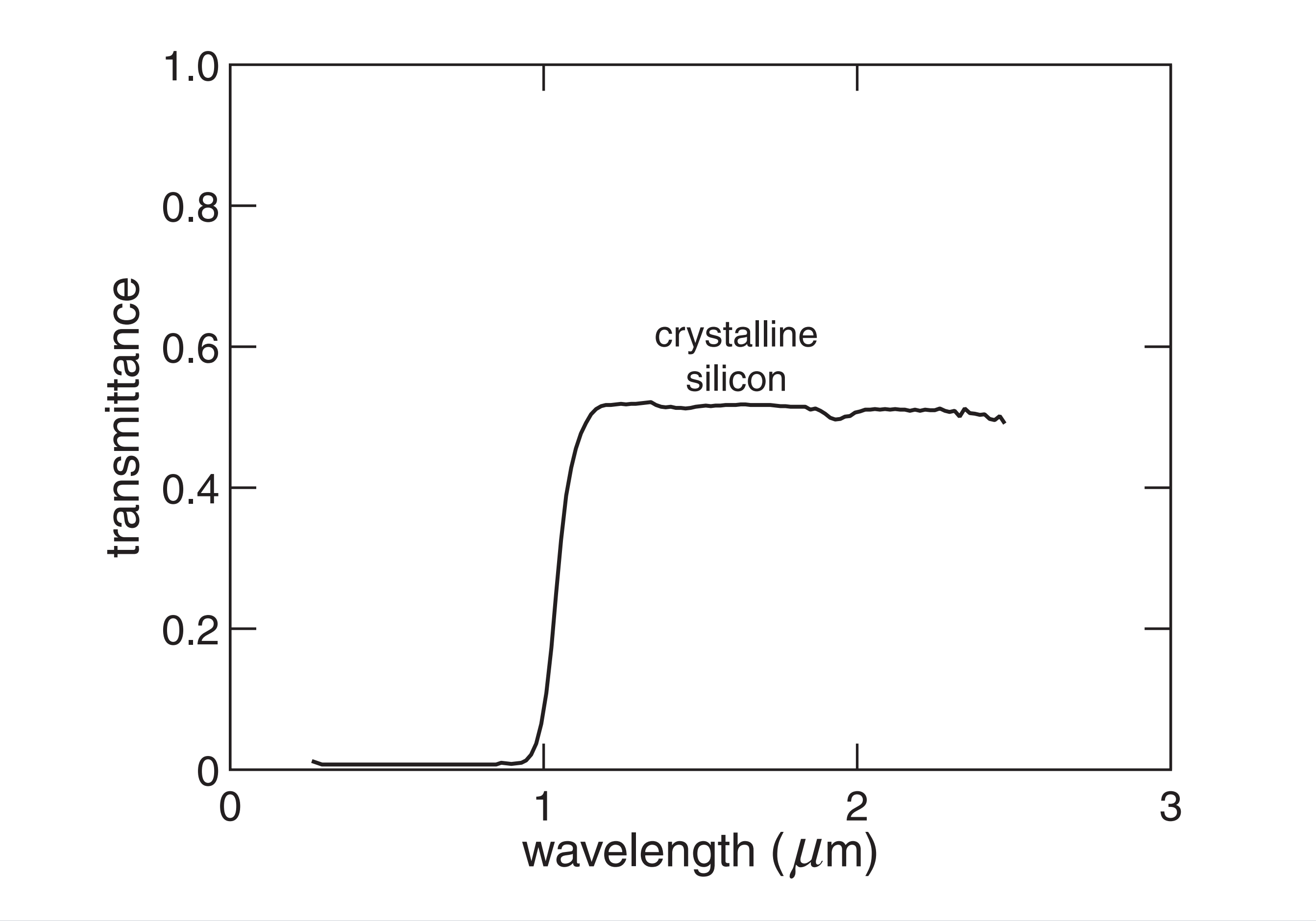
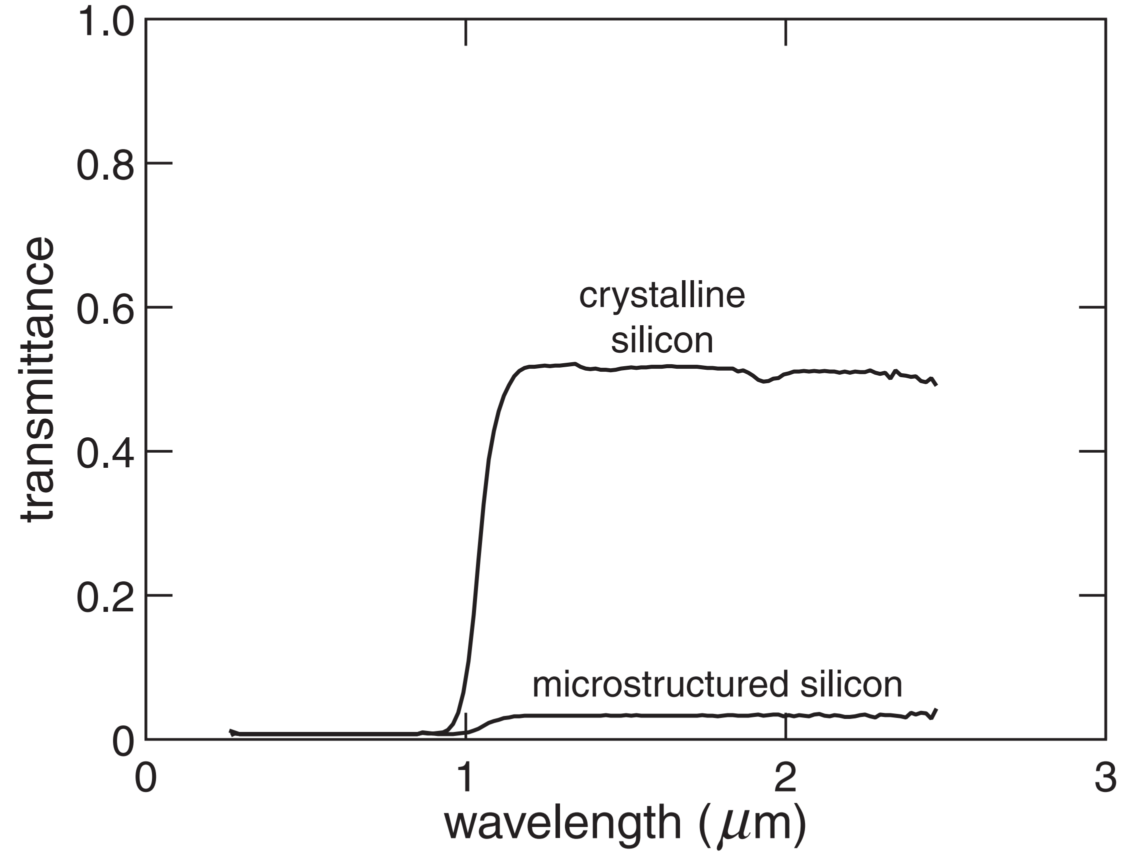


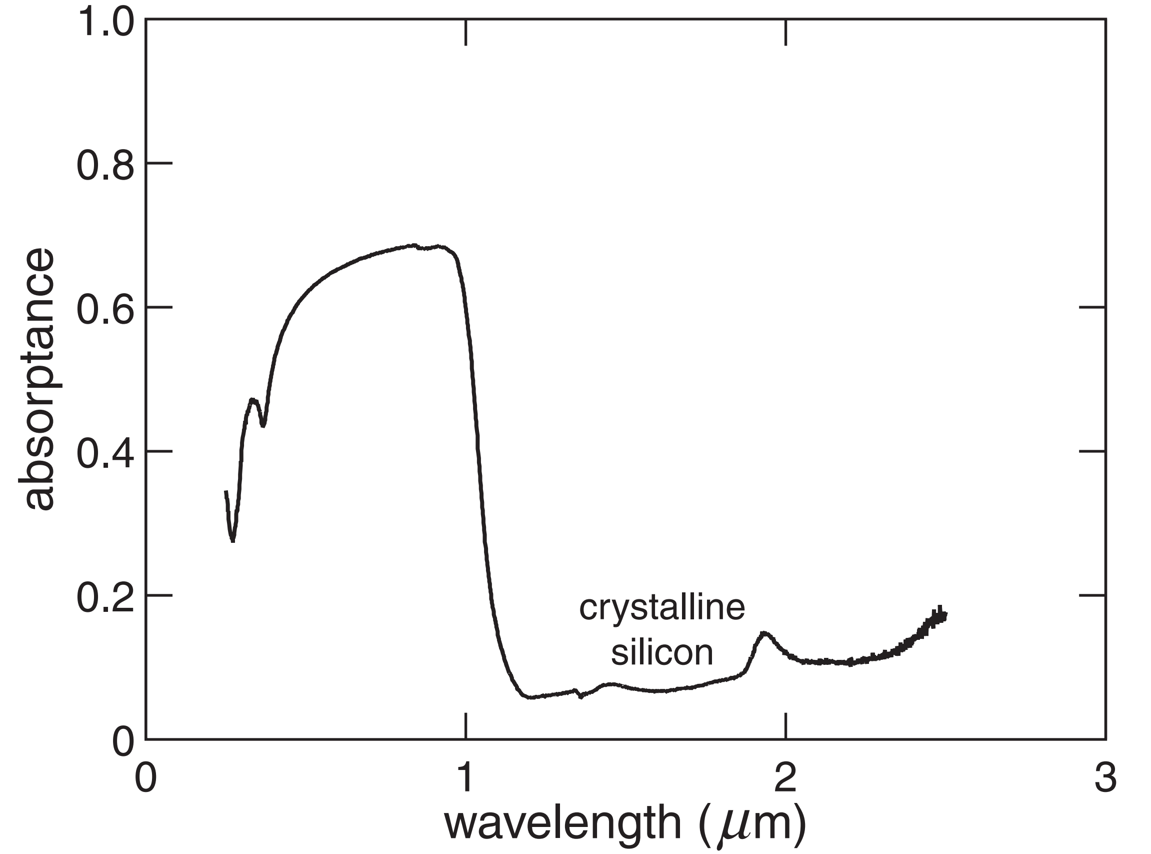
transmittance (integrating sphere)



transmittance (integrating sphere)



absorptance (1 – *R* – *T*)



Properties

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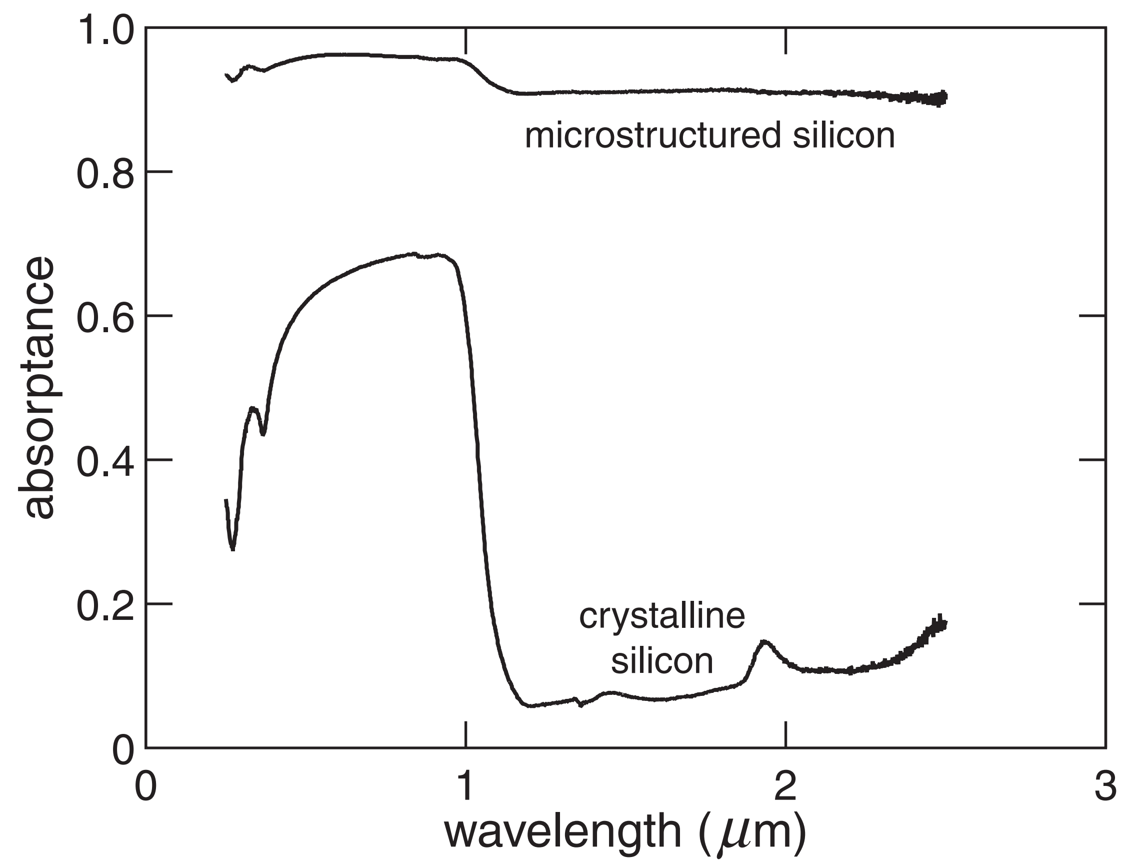

***Appl. Phys. Lett*. 78**, 1850 (2001)

Properties

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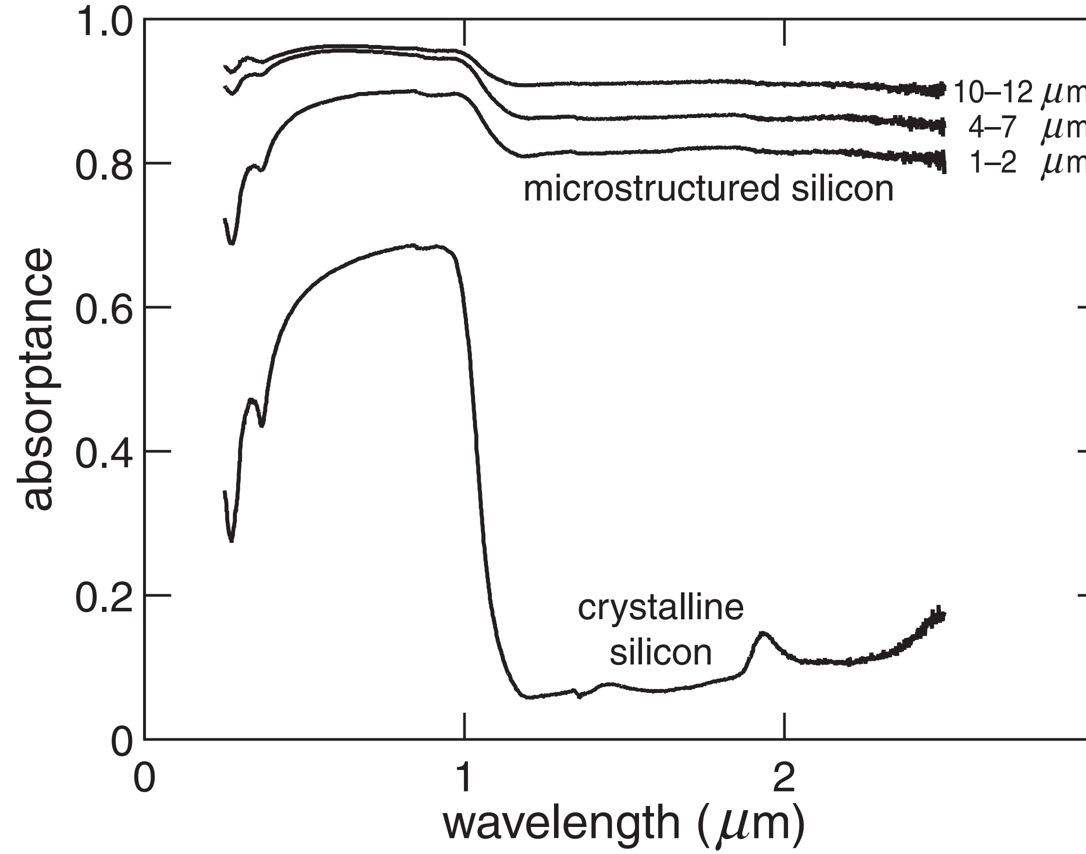

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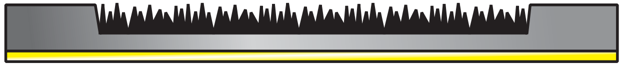
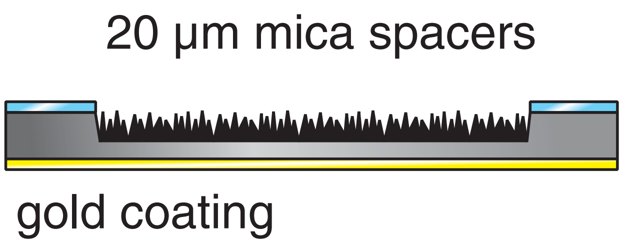
field emission setup

field emission setup

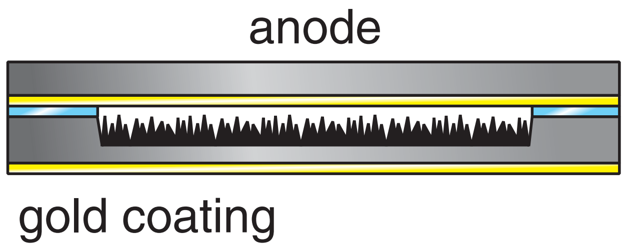


field emission setup

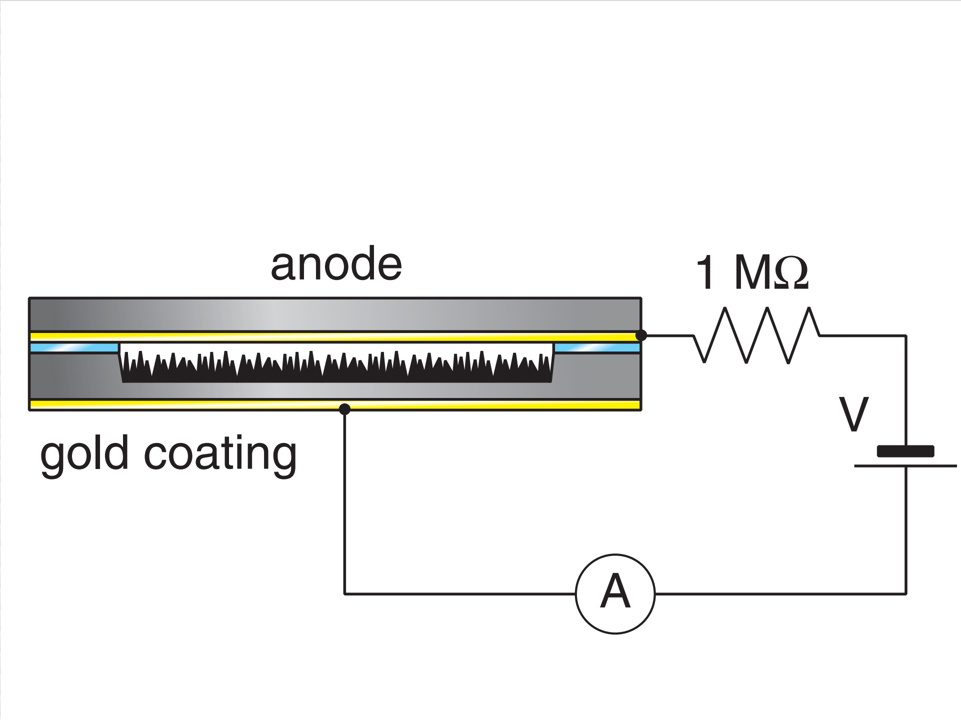


Properties

field emission setup



field emission setup



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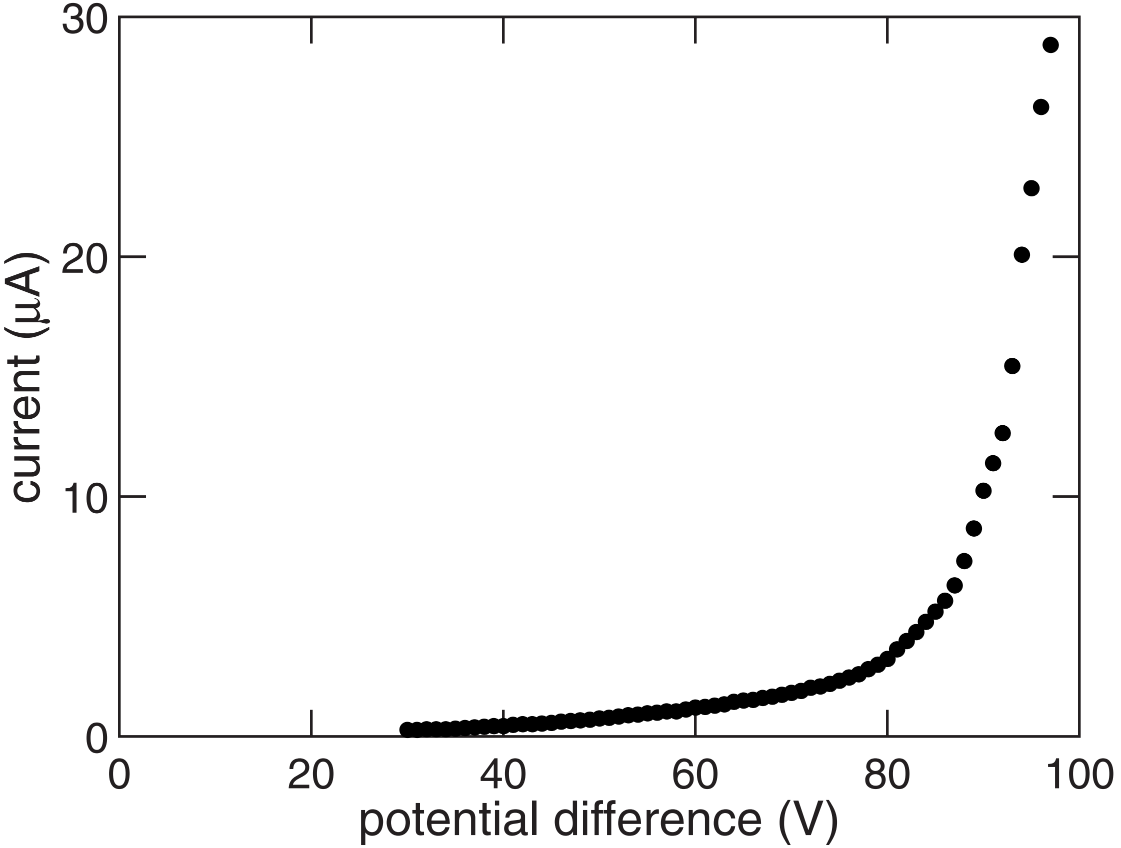
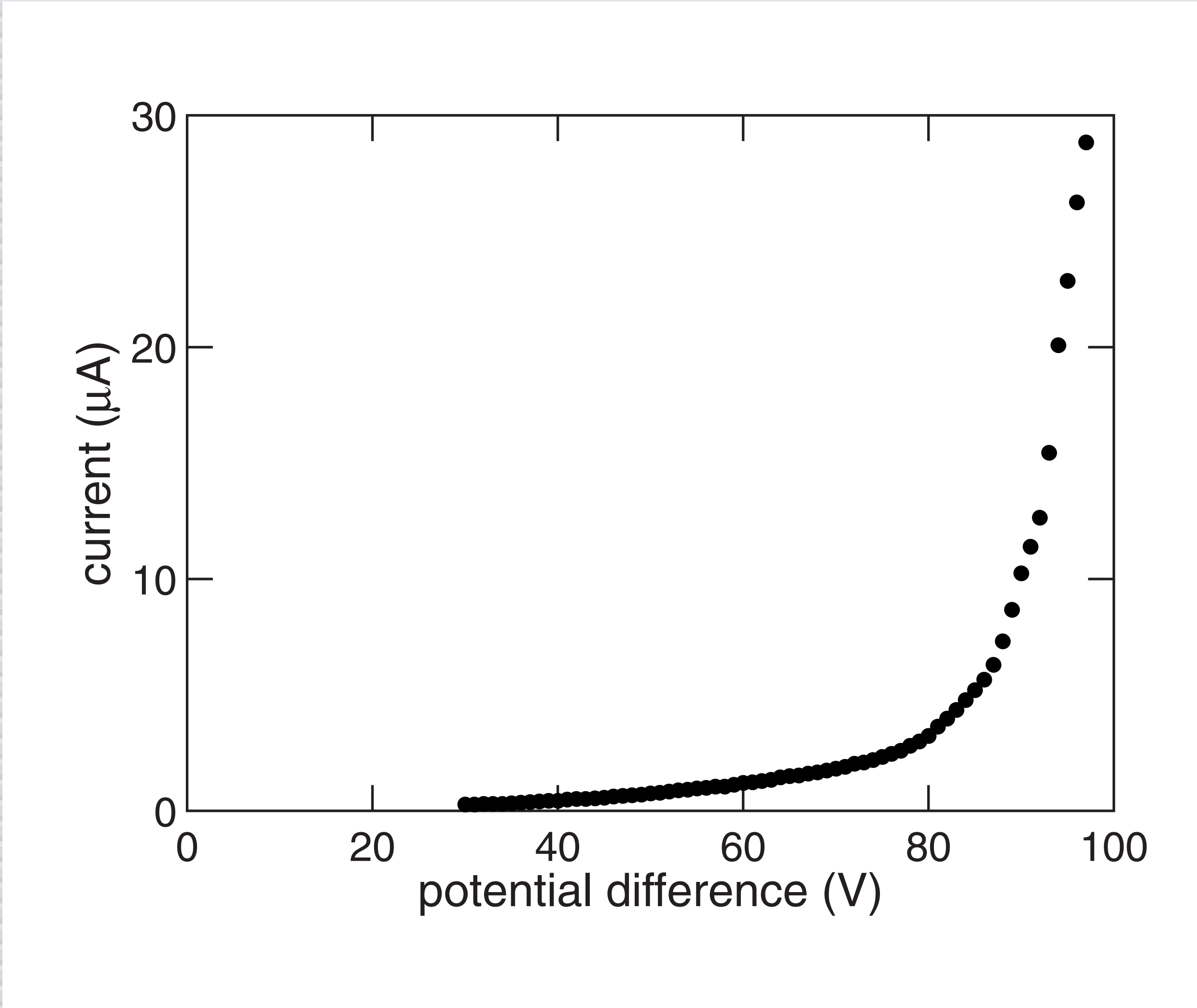
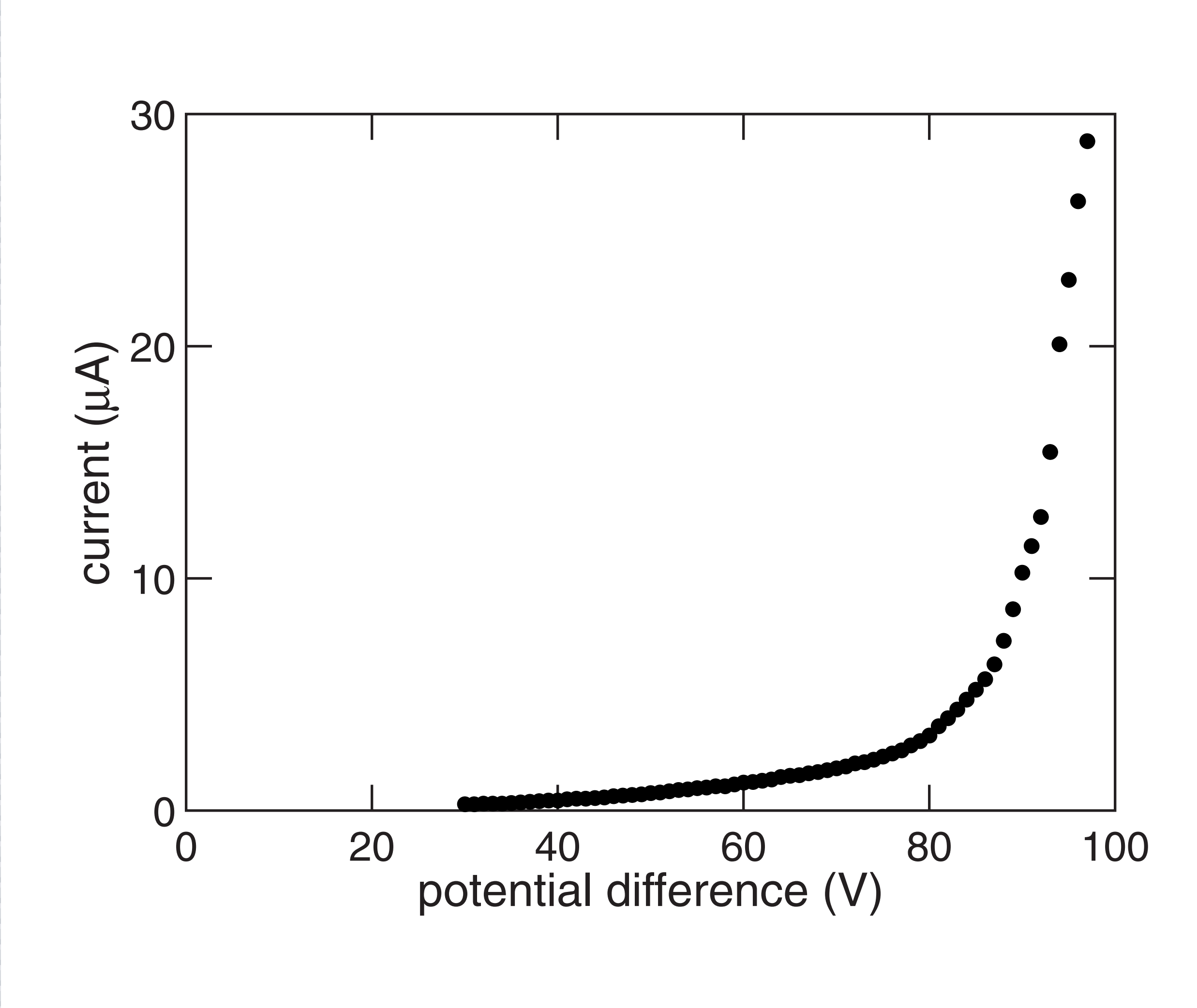


Properties



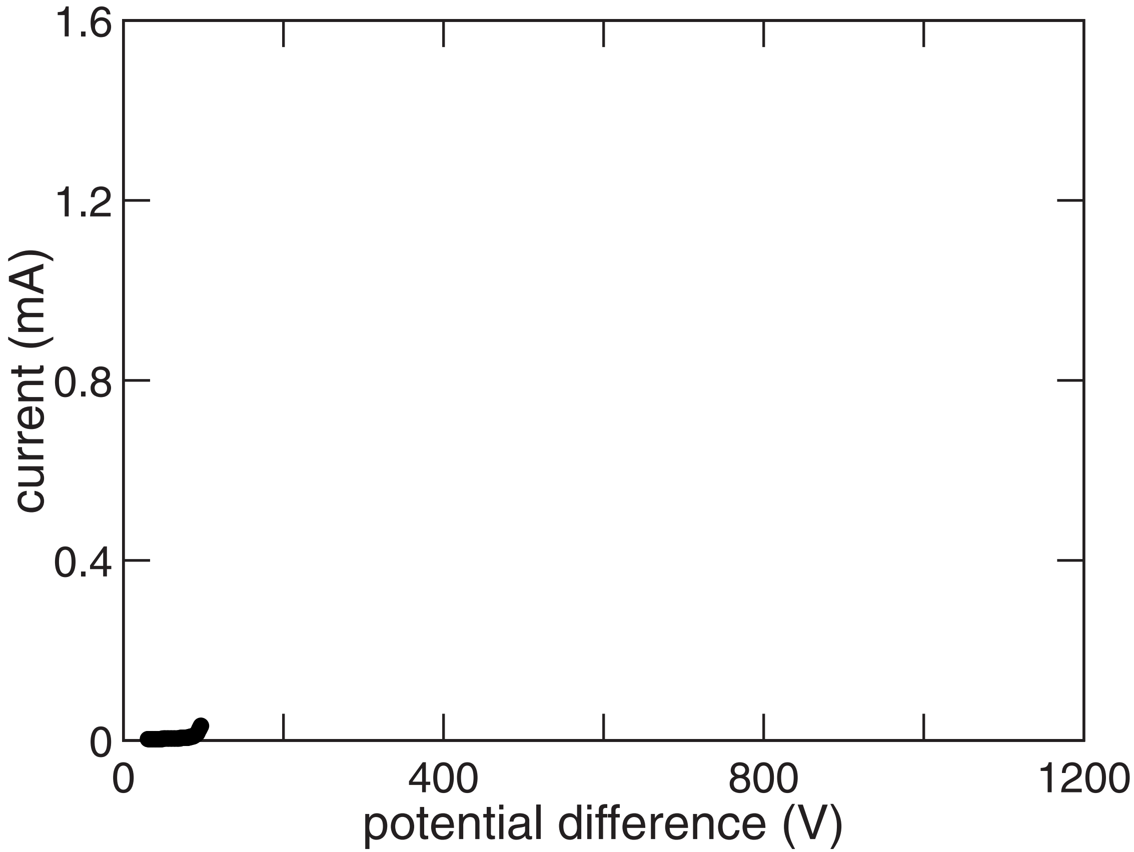
turn-on field (1 μA/cm^2): 1.2 V/μm

Properties



threshold field (10 μA/cm^2): 2.1 V/μm

Properties



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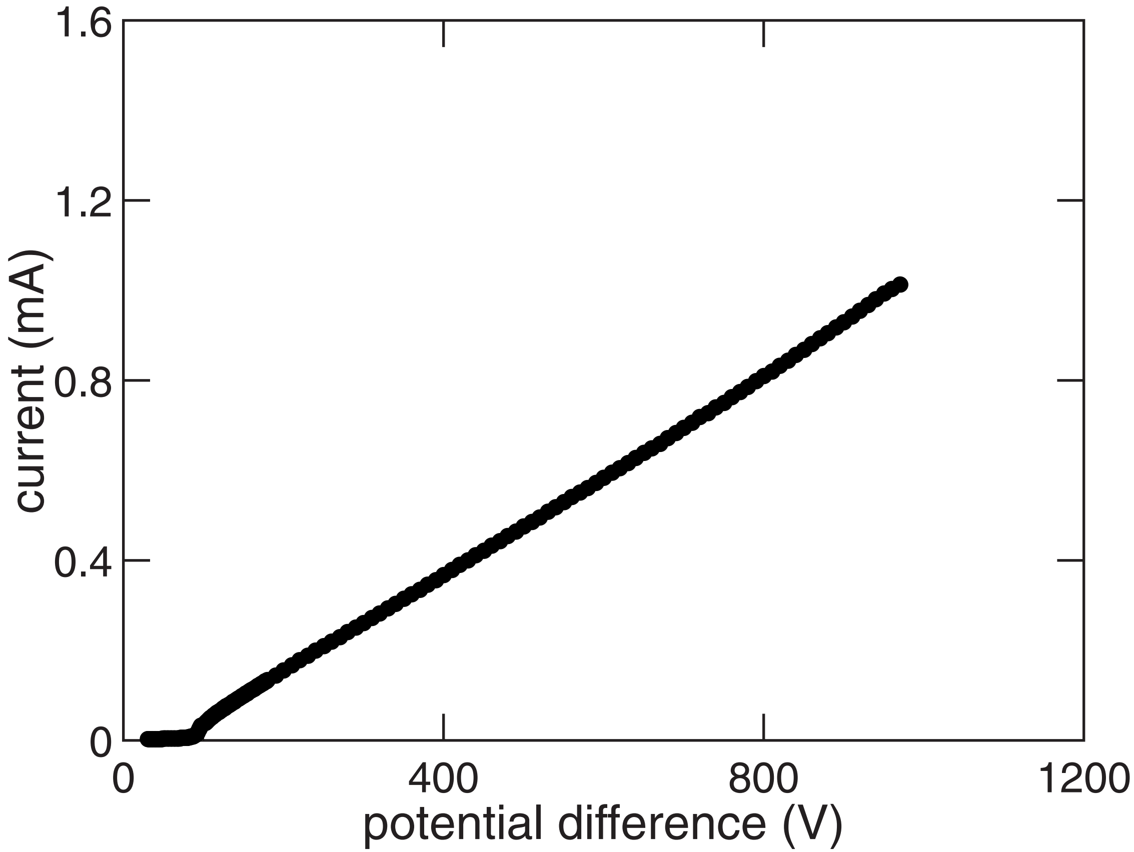

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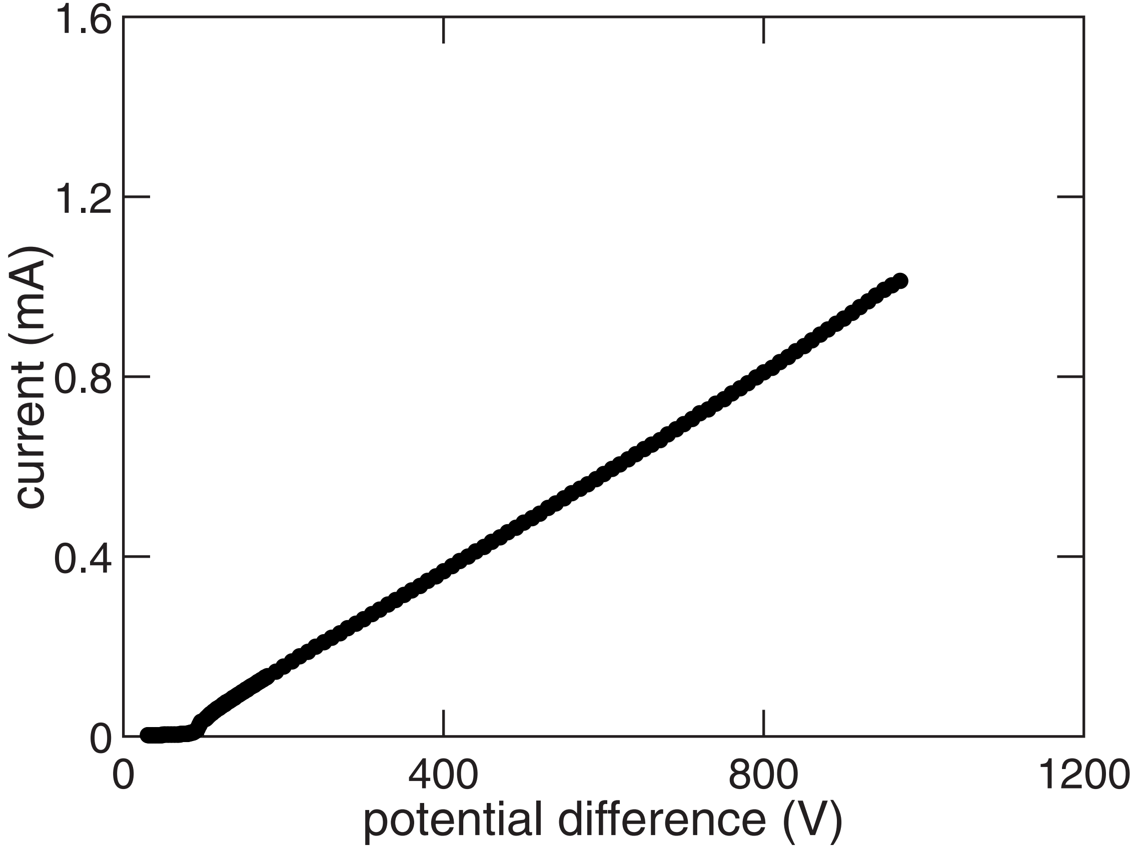


maximum current: 20 mA (4 mm^2 sample)

Properties

Points to keep in mind:

- near unity absorption
- sub-band gap absorption
- IR photoelectron generation
- high field emission at low fields

Outline

- Properties
- **Structural and chemical analysis**
- Outlook

Structural and chemical analysis

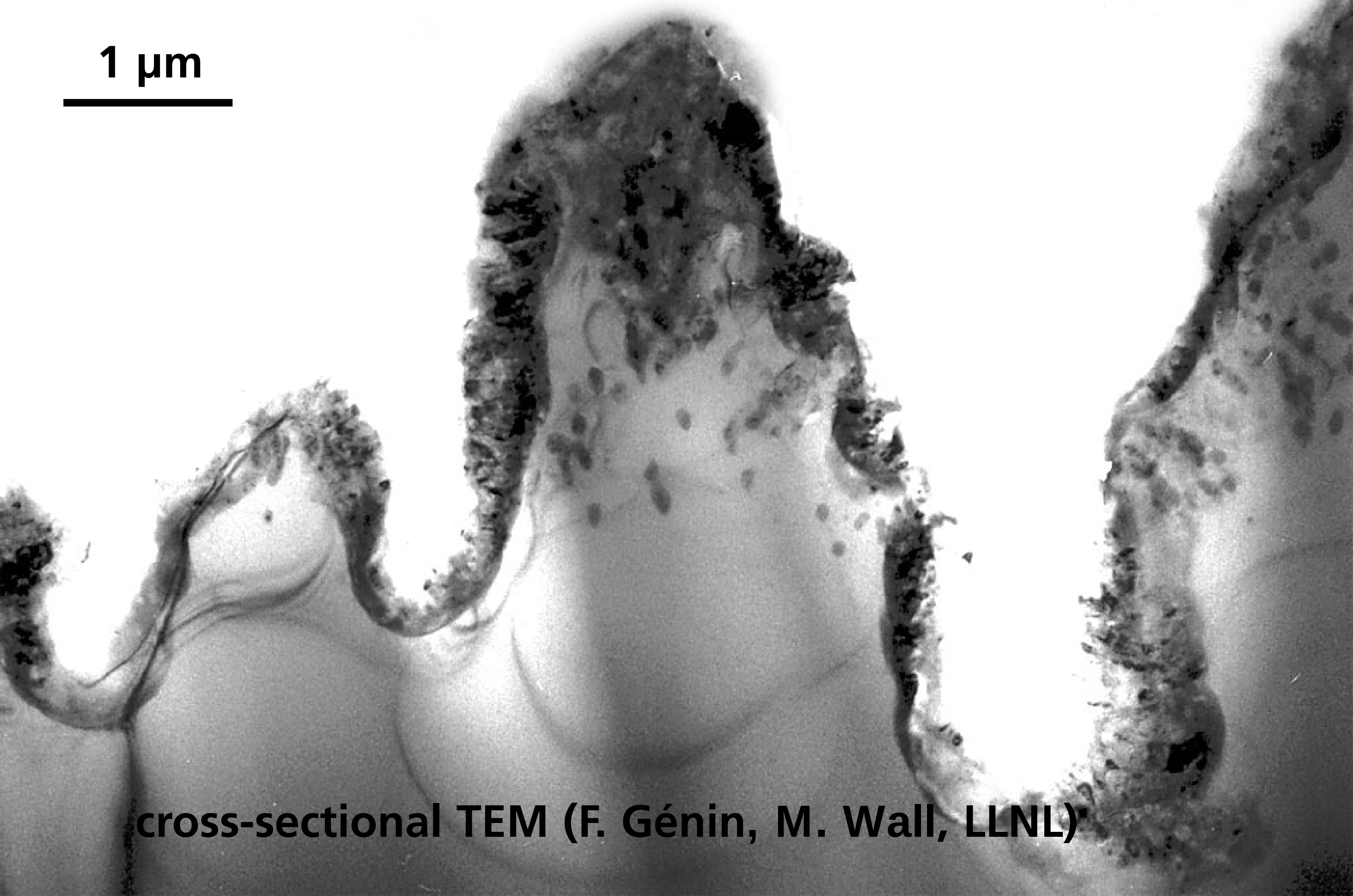
- **What causes these properties?**
- **Other gases?**

Structural and chemical analysis

Secondary ion mass spectrometry:

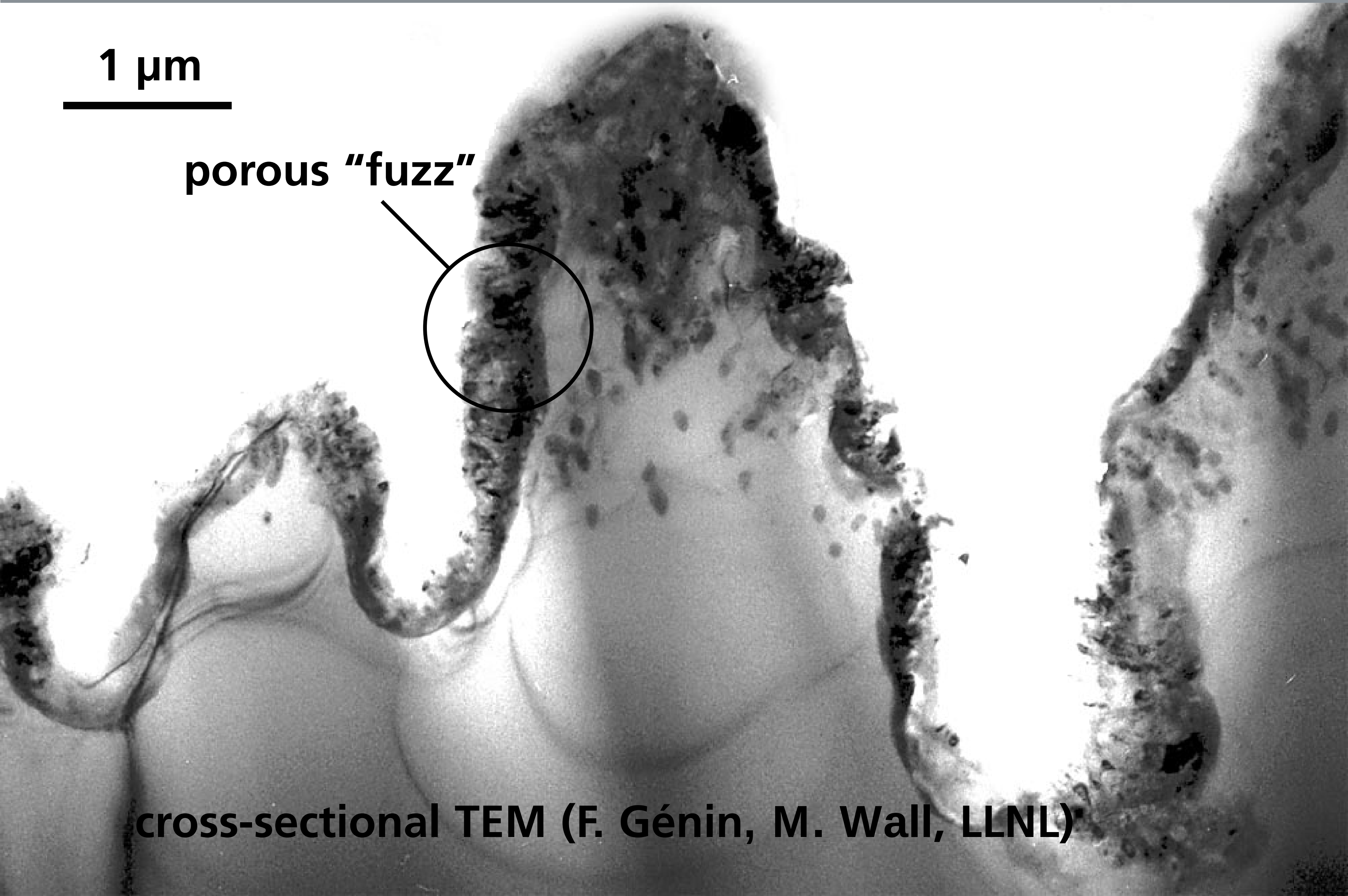
- **10^{20} cm^{-3} sulfur**
- **10^{17} cm^{-3} fluorine**

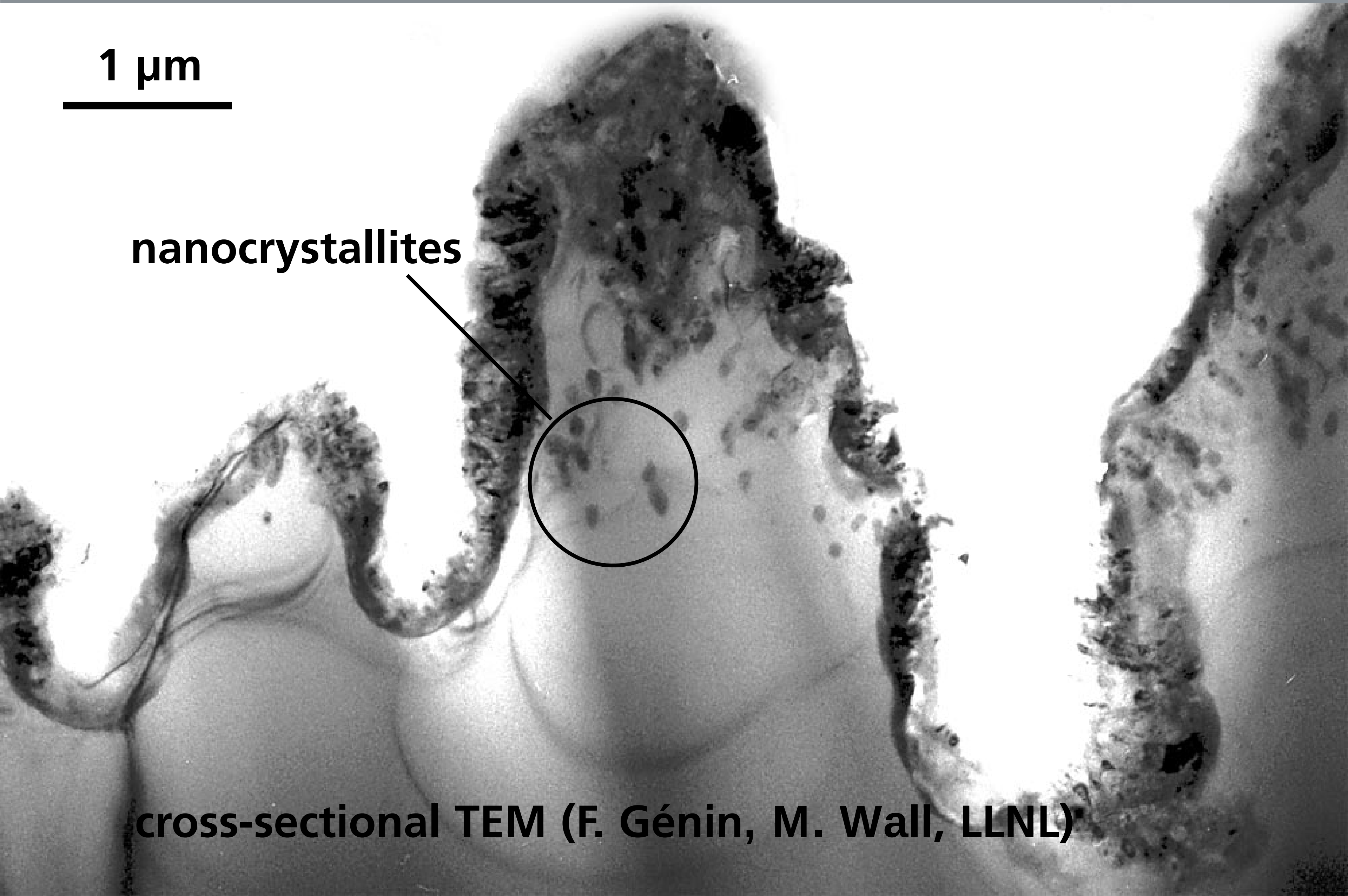
Structural and chemical analysis



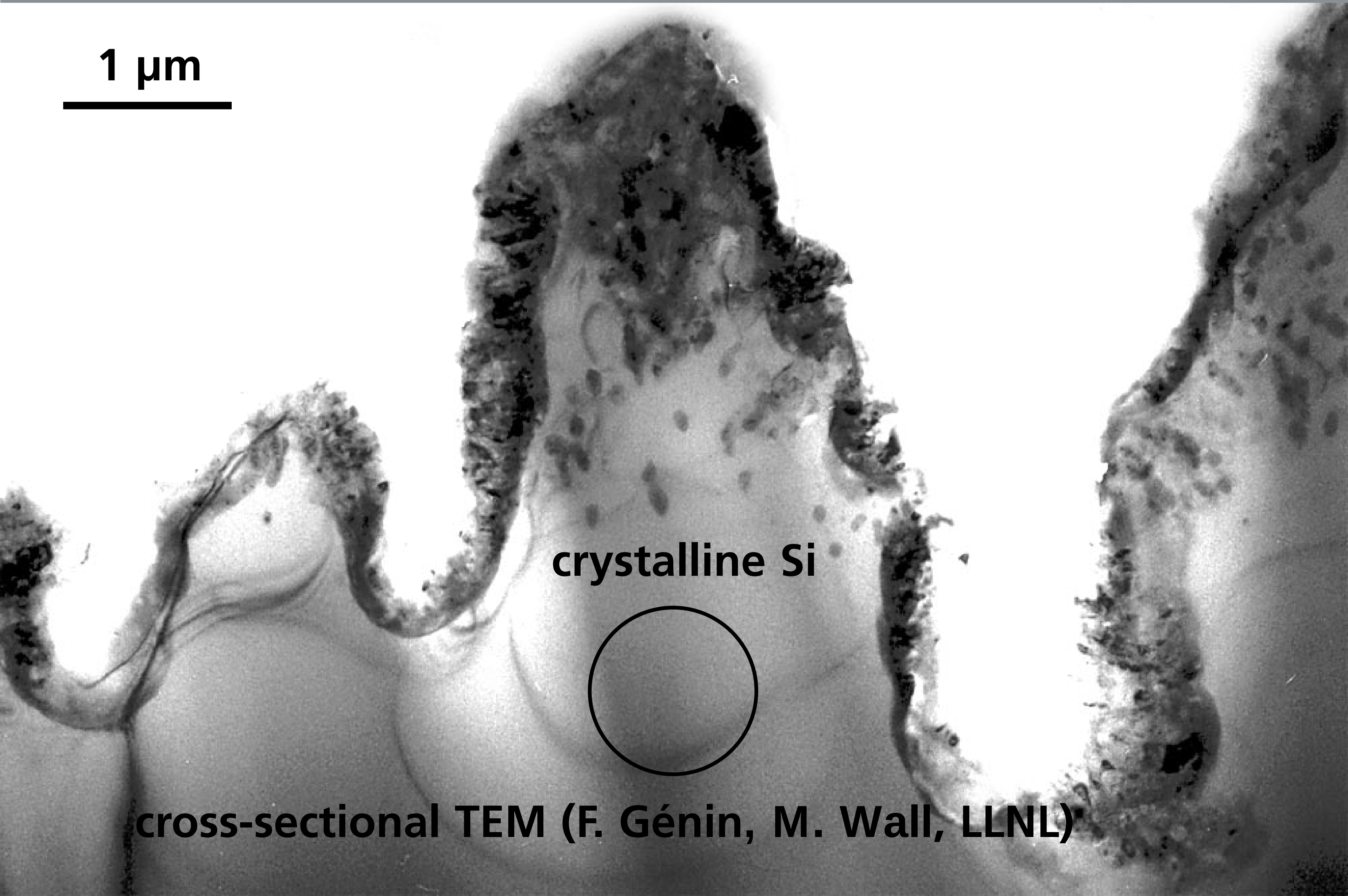
cross-sectional TEM (F. Génin, M. Wall, LLNL)

Structural and chemical analysis




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

Structural and chemical analysis



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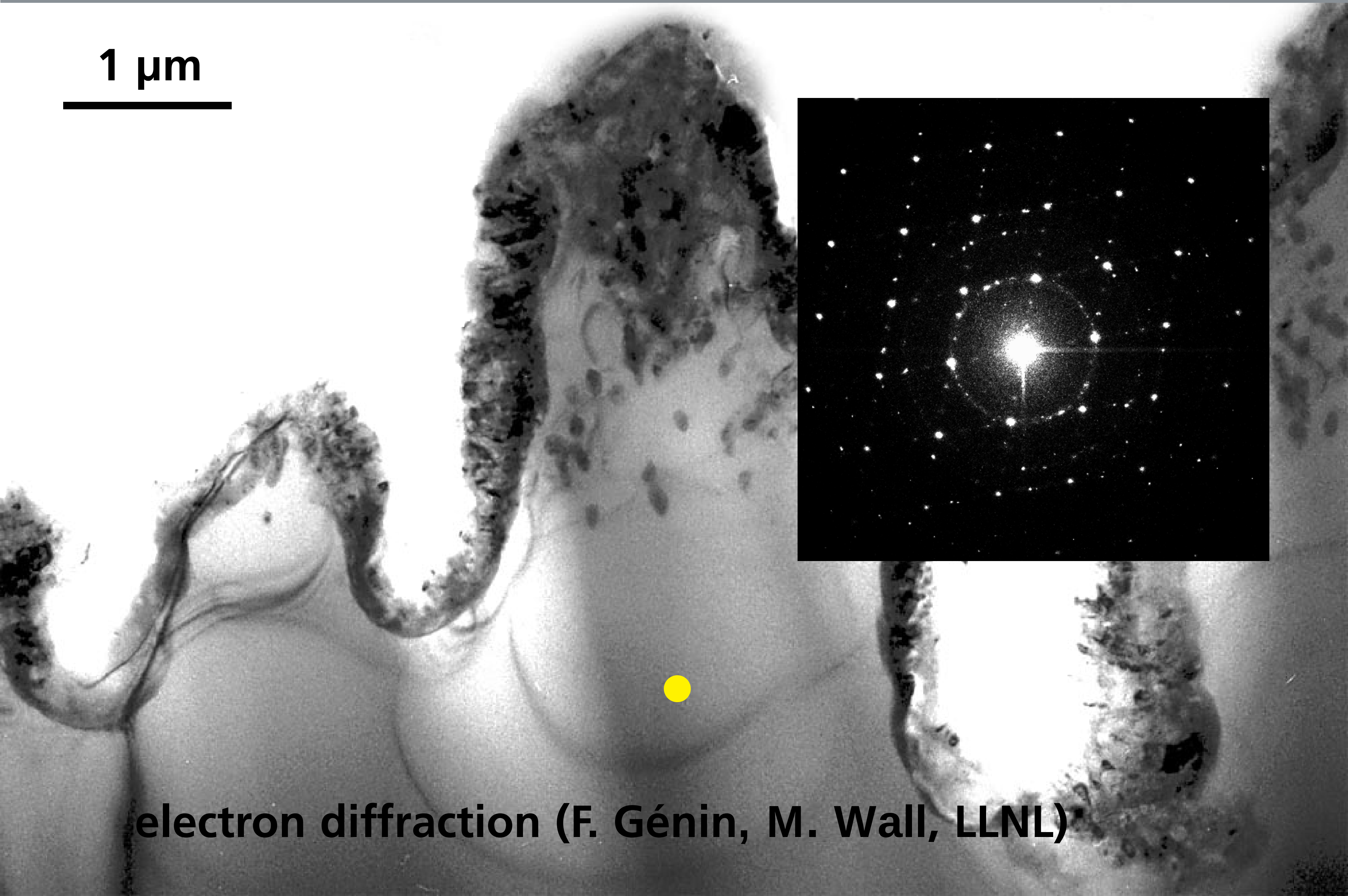
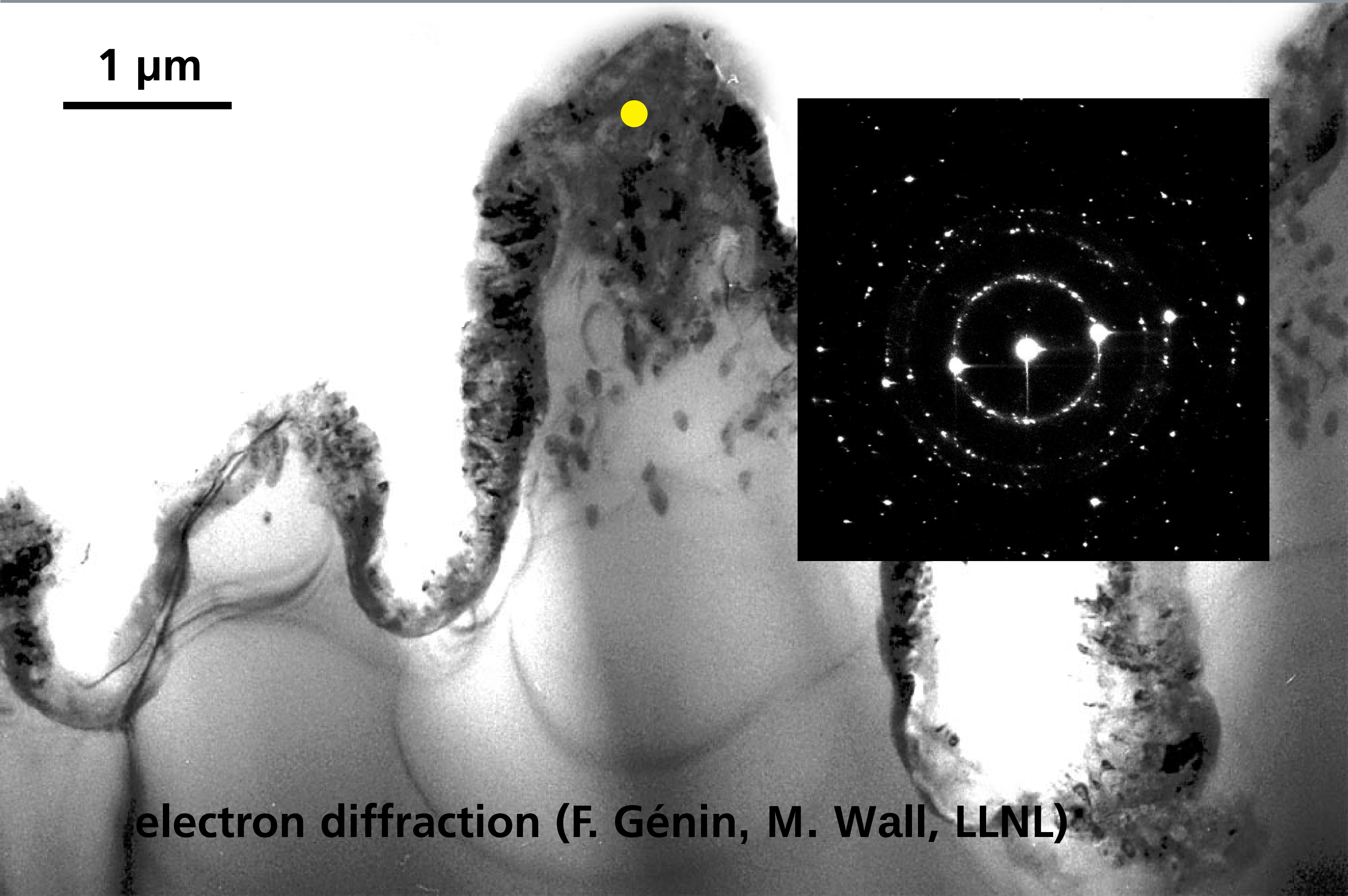


electron diffraction (F. Génin, M. Wall, LLNL)

Structural and chemical analysis



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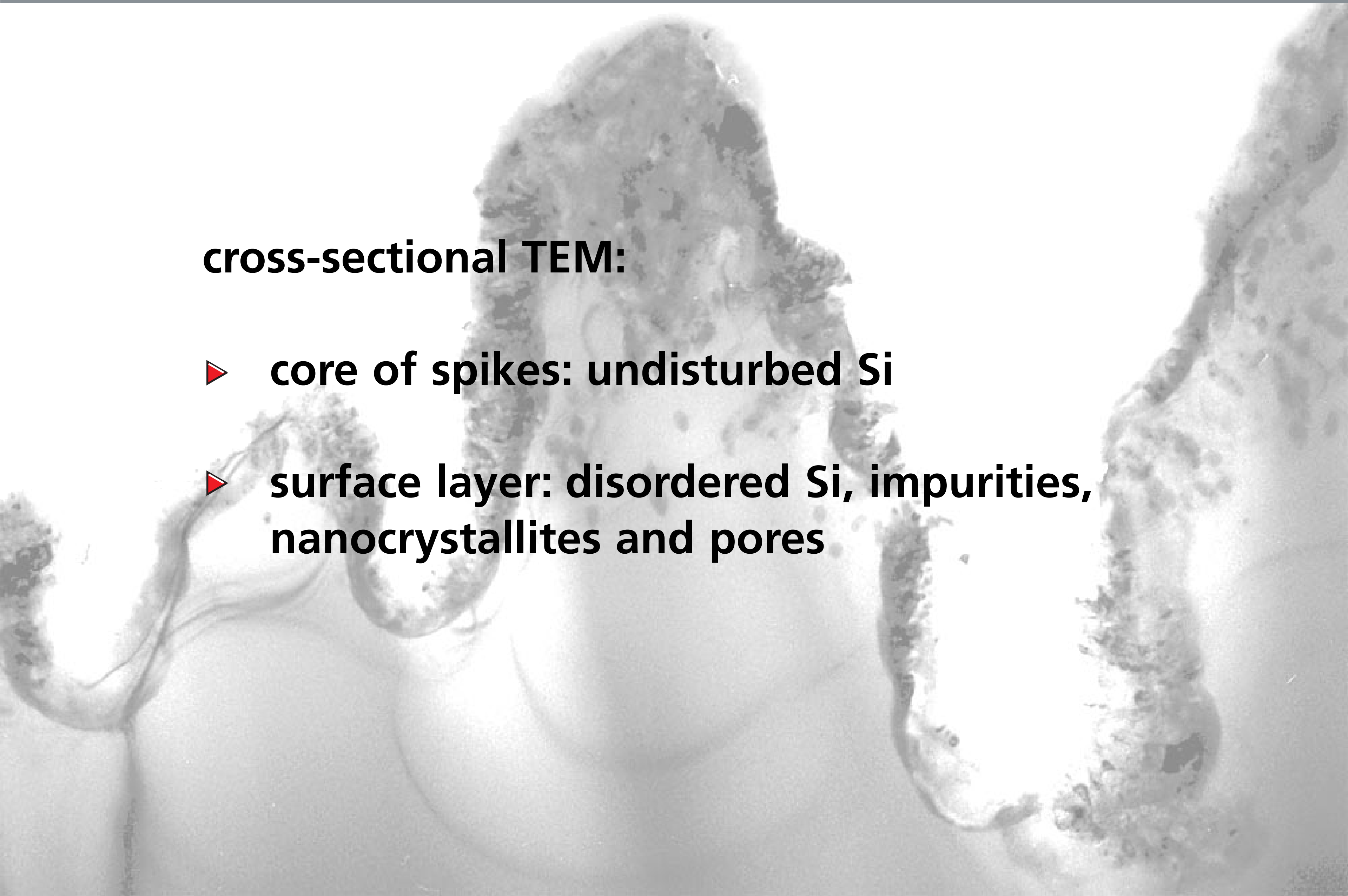
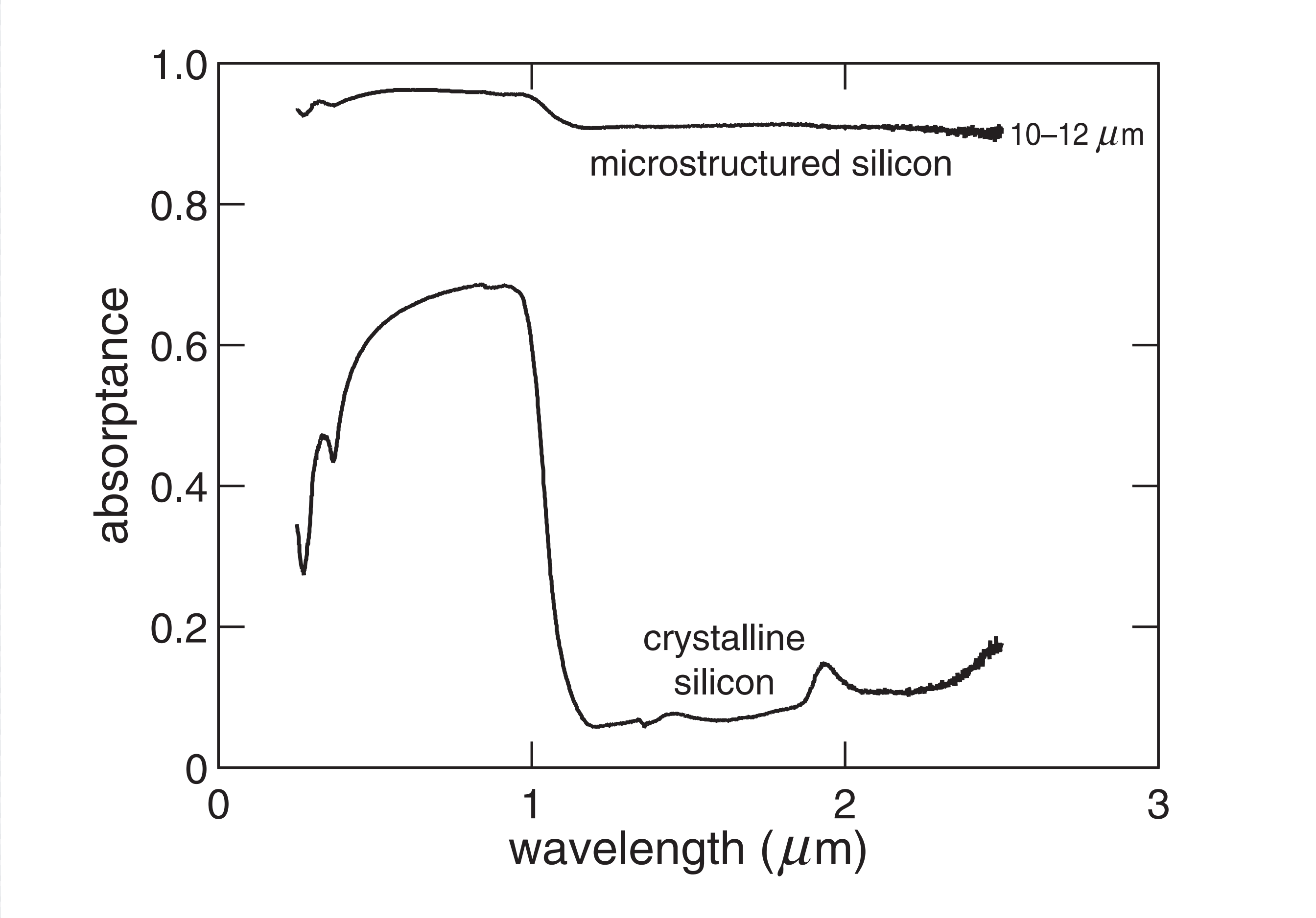


cross-sectional TEM:

- core of spikes: undisturbed Si
- surface layer: disordered Si, impurities, nanocrystallites and pores

Structural and chemical analysis

anneal 4 hours at 1200 K



***Appl. Phys. Lett*. 78, 1850 (2001)**

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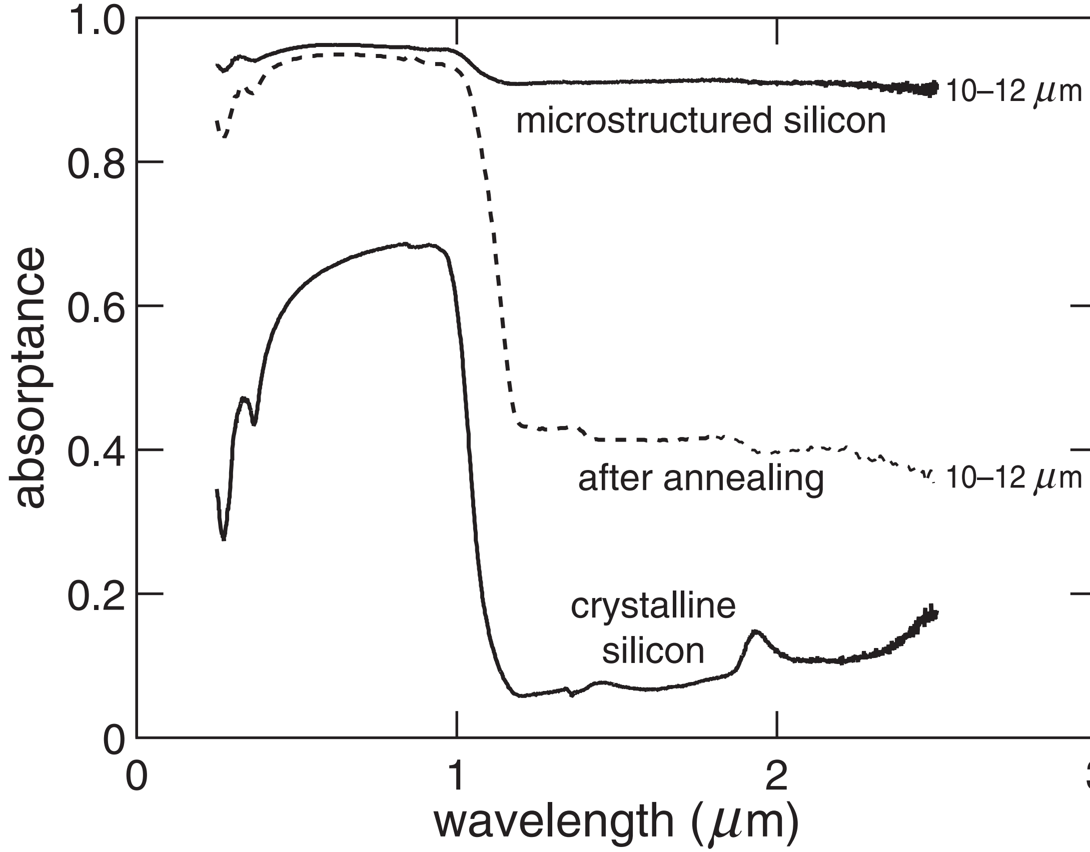

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Structural and chemical analysis

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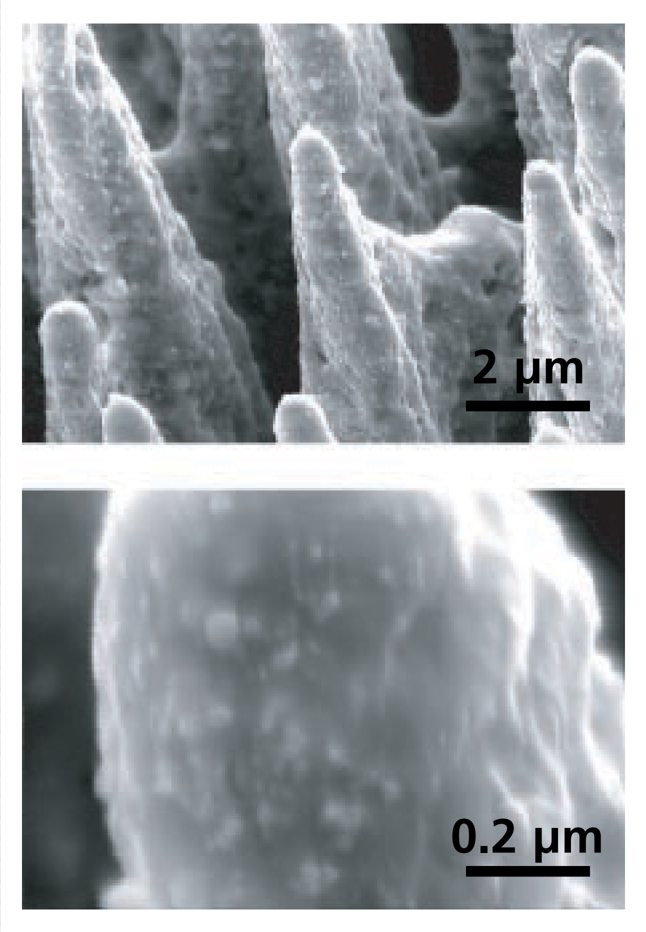

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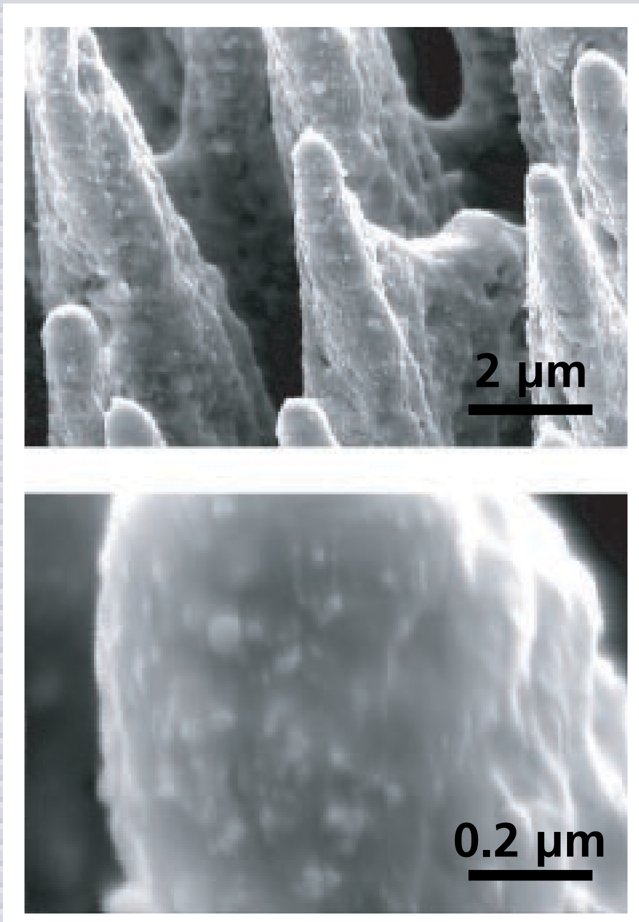

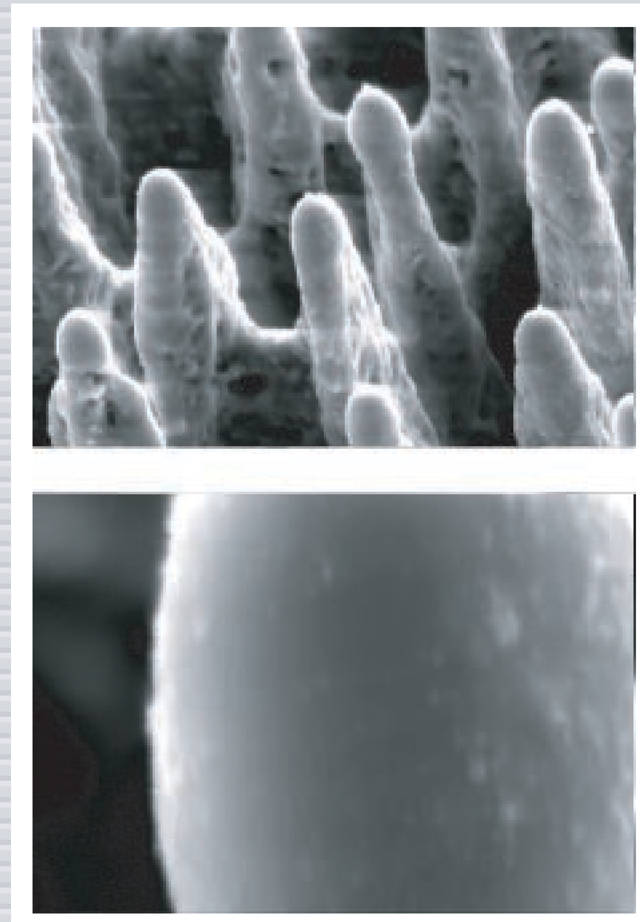

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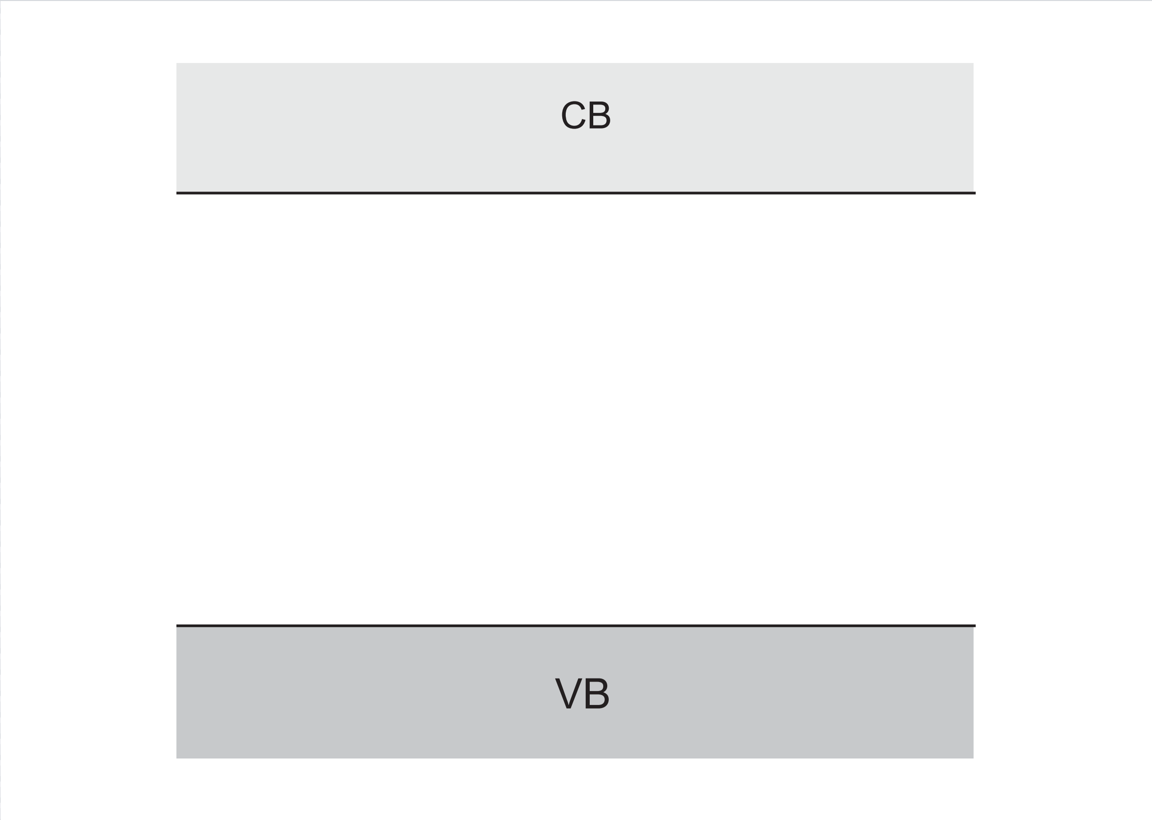
Structural and chemical analysis

Effects of annealing:

- **IR absorption: reduced twofold**
- **SEM: fewer surface nanostructures**
- **SIMS: sulfur content reduced twofold**

sulfur introduces states in the gap



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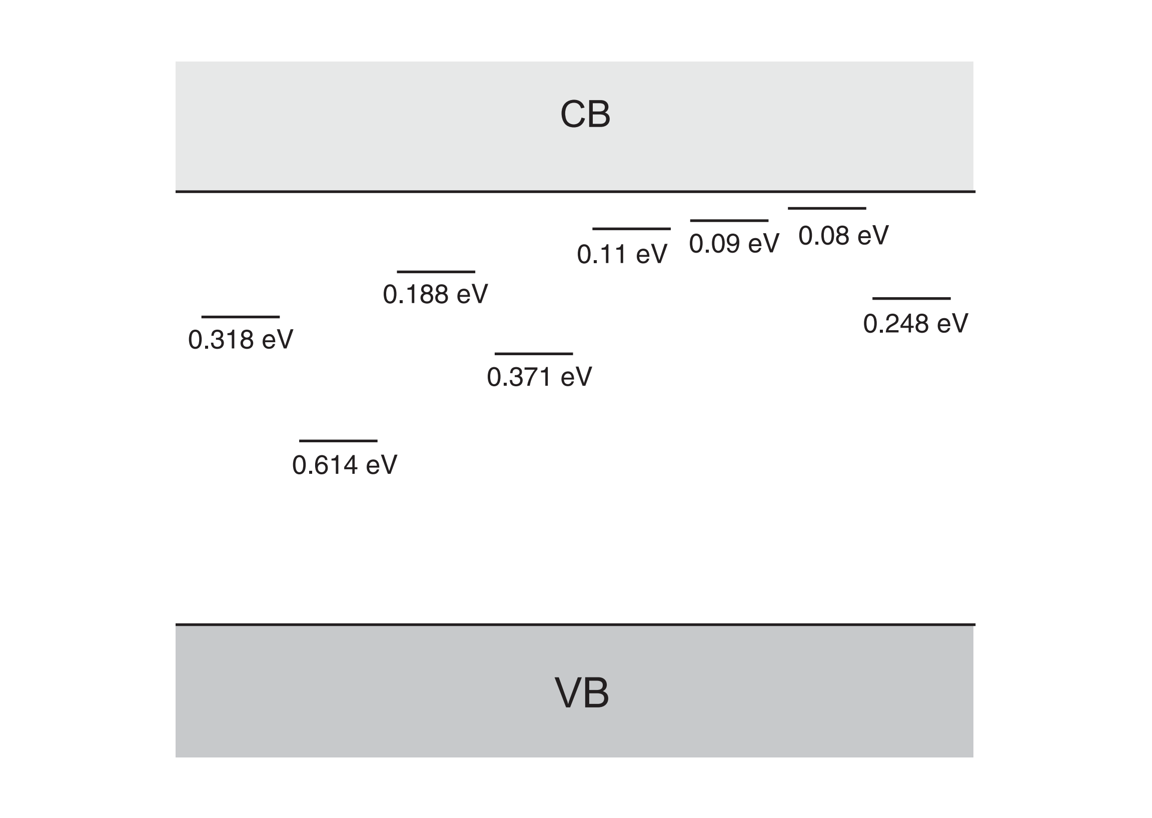
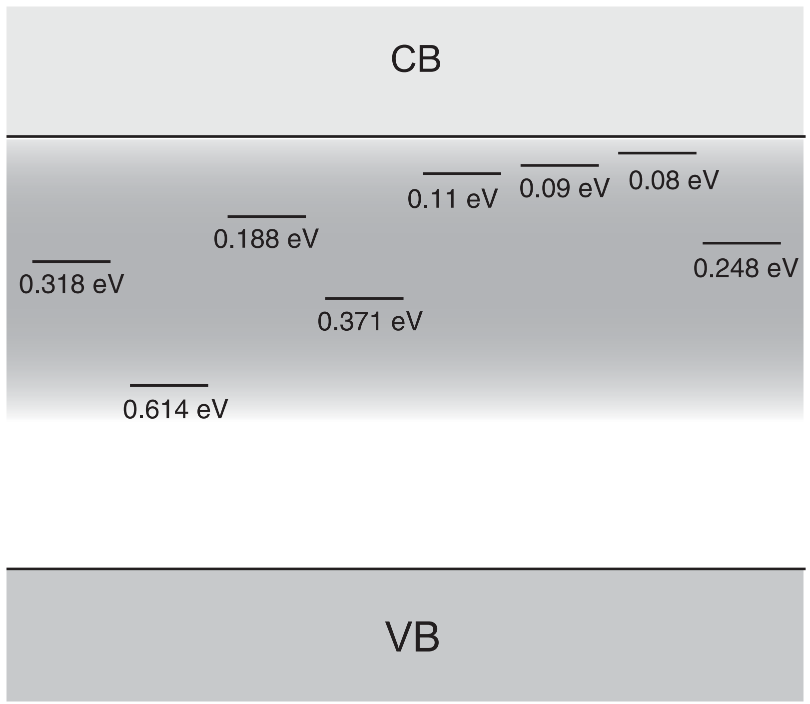
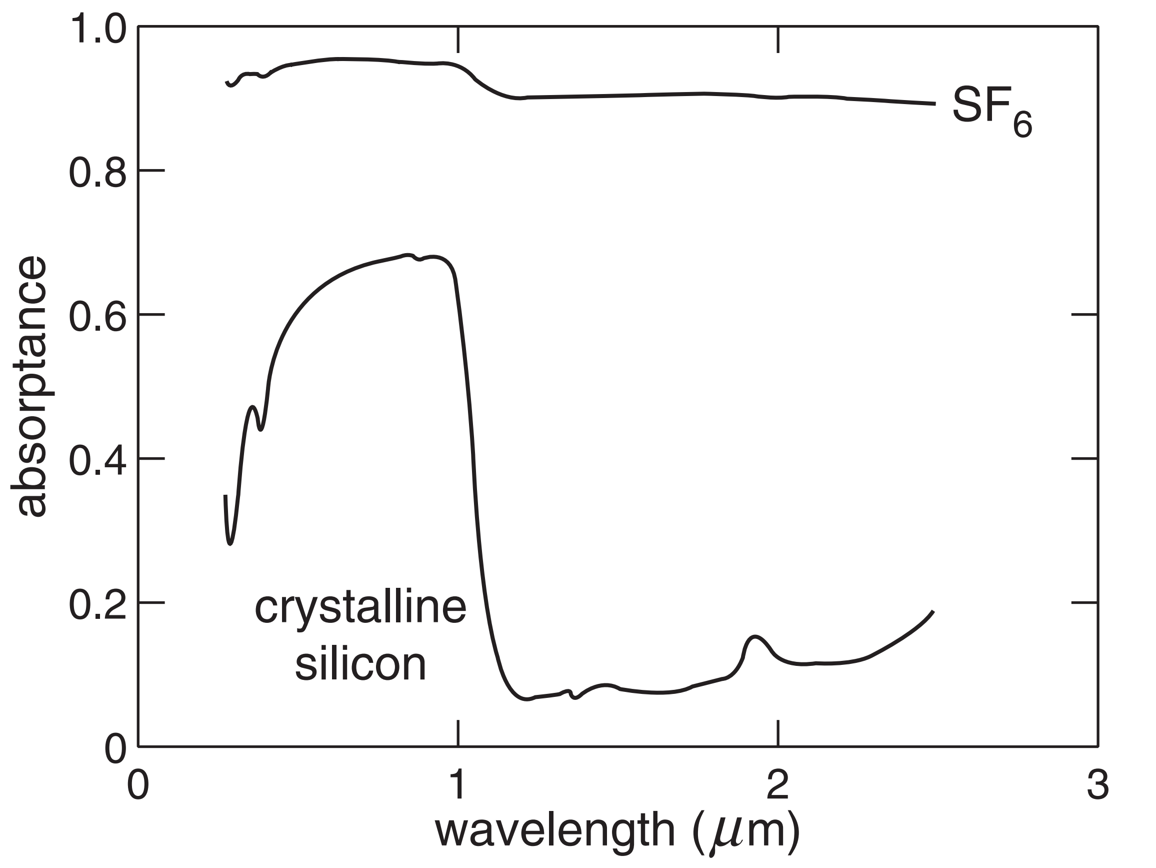


Janzén, *et al.*, *Phys. Rev. B* **29**,1907 (1984)

states broaden into a band



effect of ambient gas on absorptance



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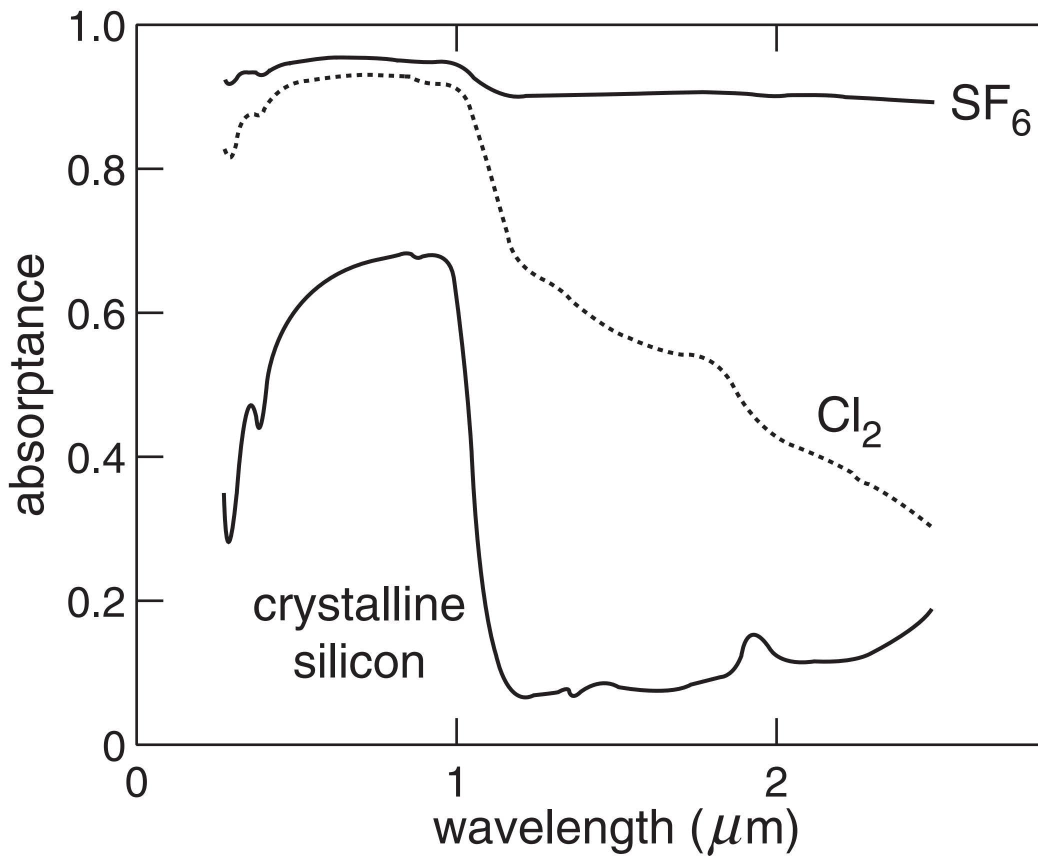

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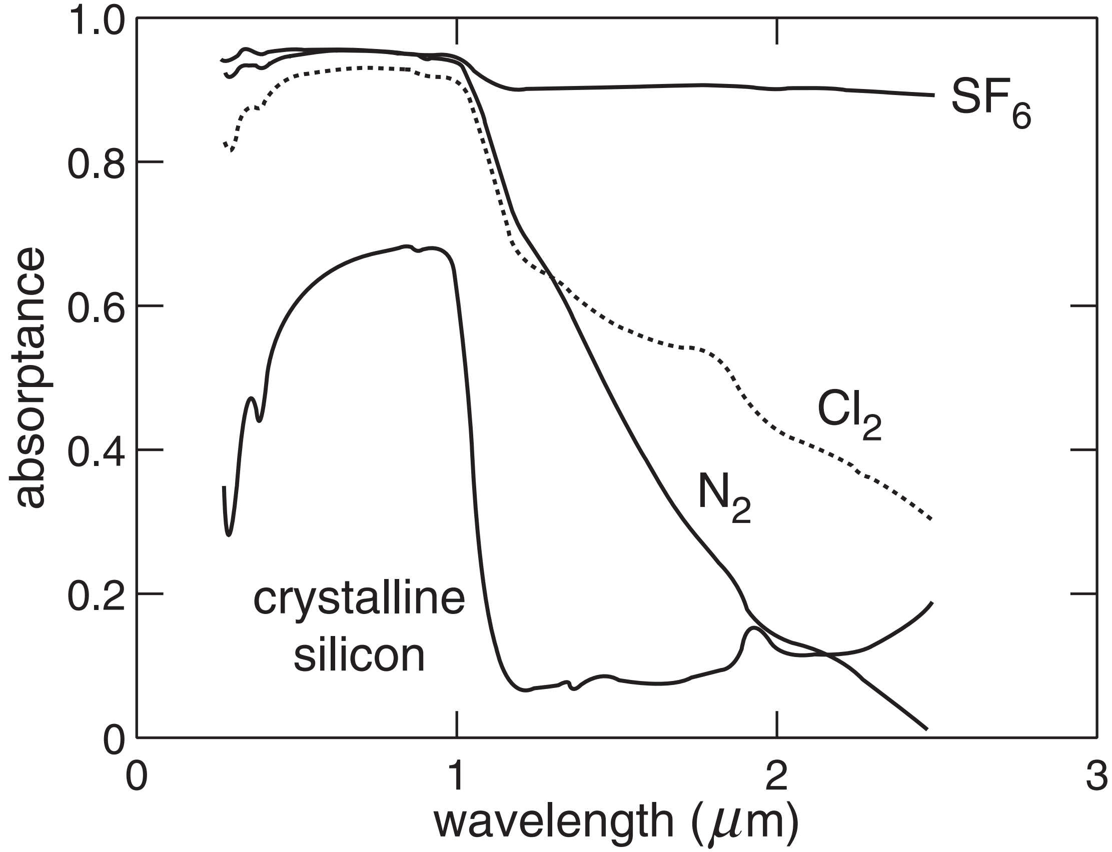

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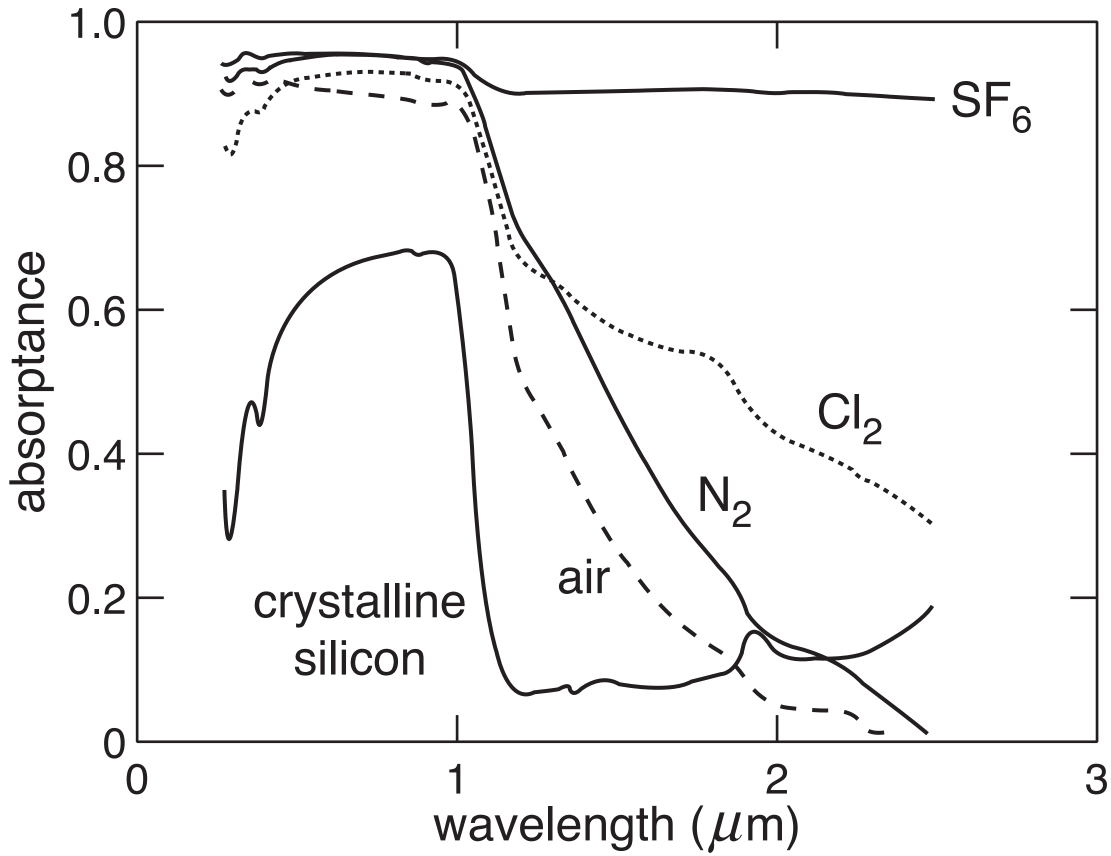

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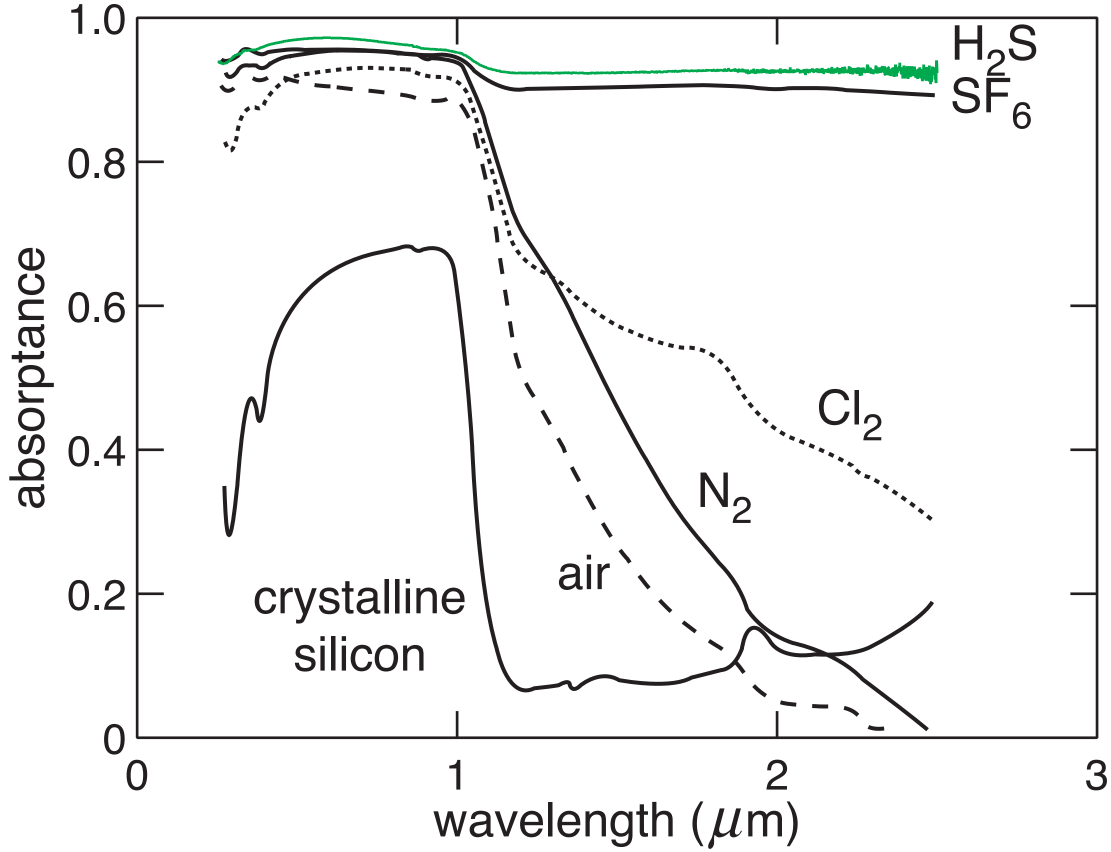

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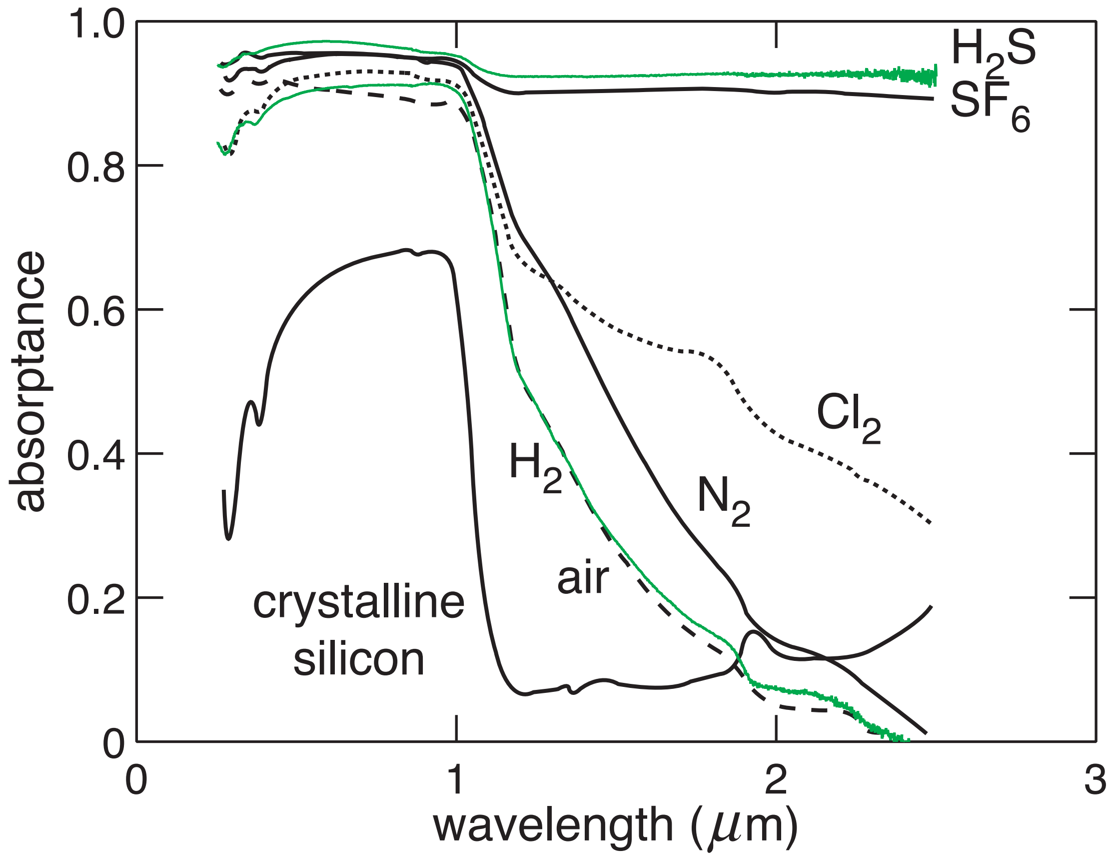


Structural and chemical analysis

- significant incorporation of ambient species
- nanostructured surface layer
- sulfur content correlates with IR absorption

Outline

- Properties
- Structural and chemical analysis
- **Outlook**

New Scientist 13, 34 (2001)

A forest of silicon spikes could revolutionise solar cells and give you painless injections. **Bruce Schechter** peers into the mysterious world of black silicon

TALL, DARK AND STRANGER

WE ALL love stories of serendipity. They

semiconductors with a powerful laser. In the early 1990s, Mazur's was the first academic lab in the world to get its hands on a femtosecond laser. This device produces pulses of light that are hundreds

around the laboratory," he claims.

Outlook

- **detector technology**

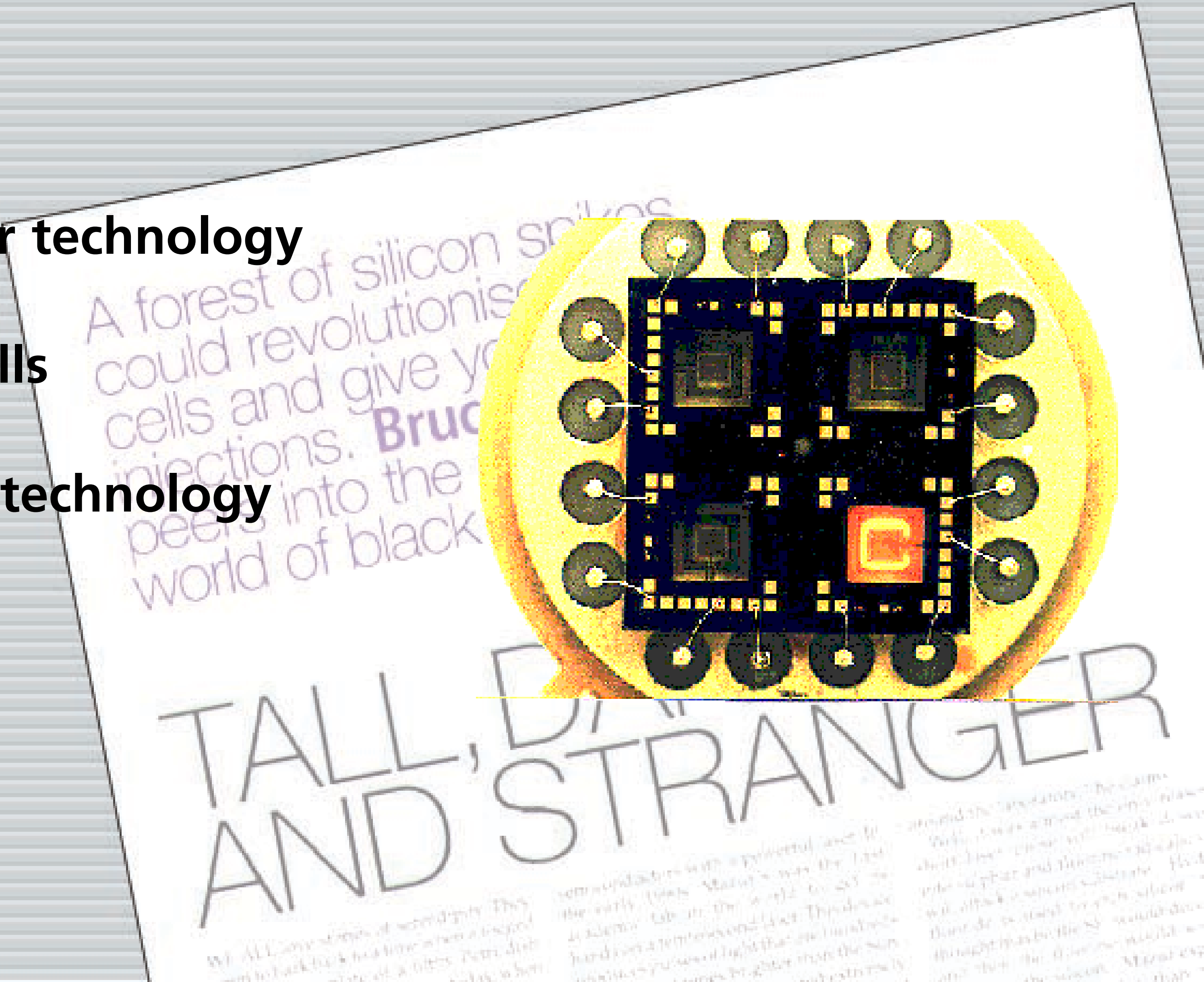
- detector technology
- solar cells

Outlook

- detector technology
- solar cells
- display technology

Outlook

- detector technology
- solar cells
- display technology
- sensors



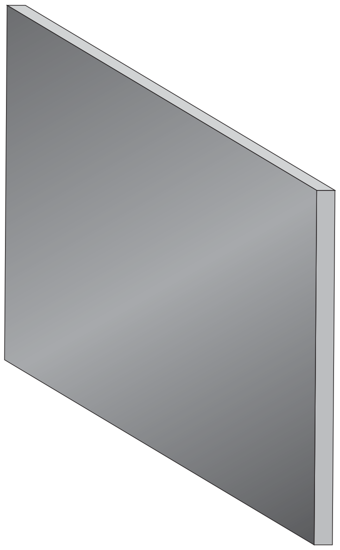
Outlook

- development of spikes
- spike formation through grids
- cell adhesion
- functionalization

Outlook

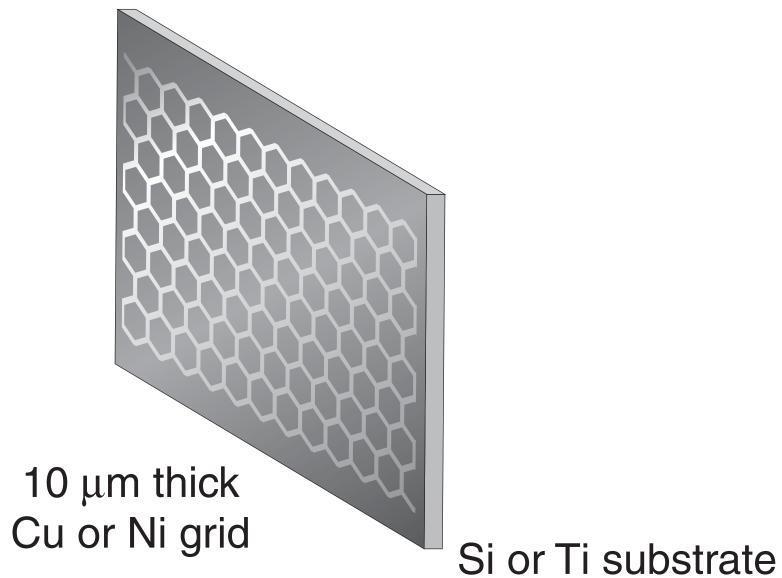
can ordering of spikes be improved by using a grid?

Outlook



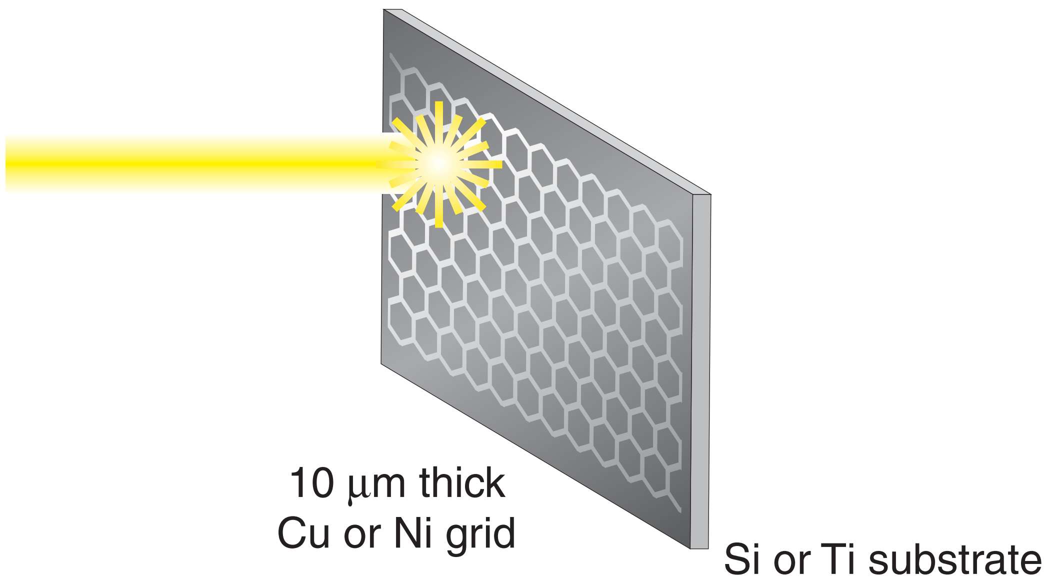
Outlook

place grid in front of substrate



Outlook

scan laser beam



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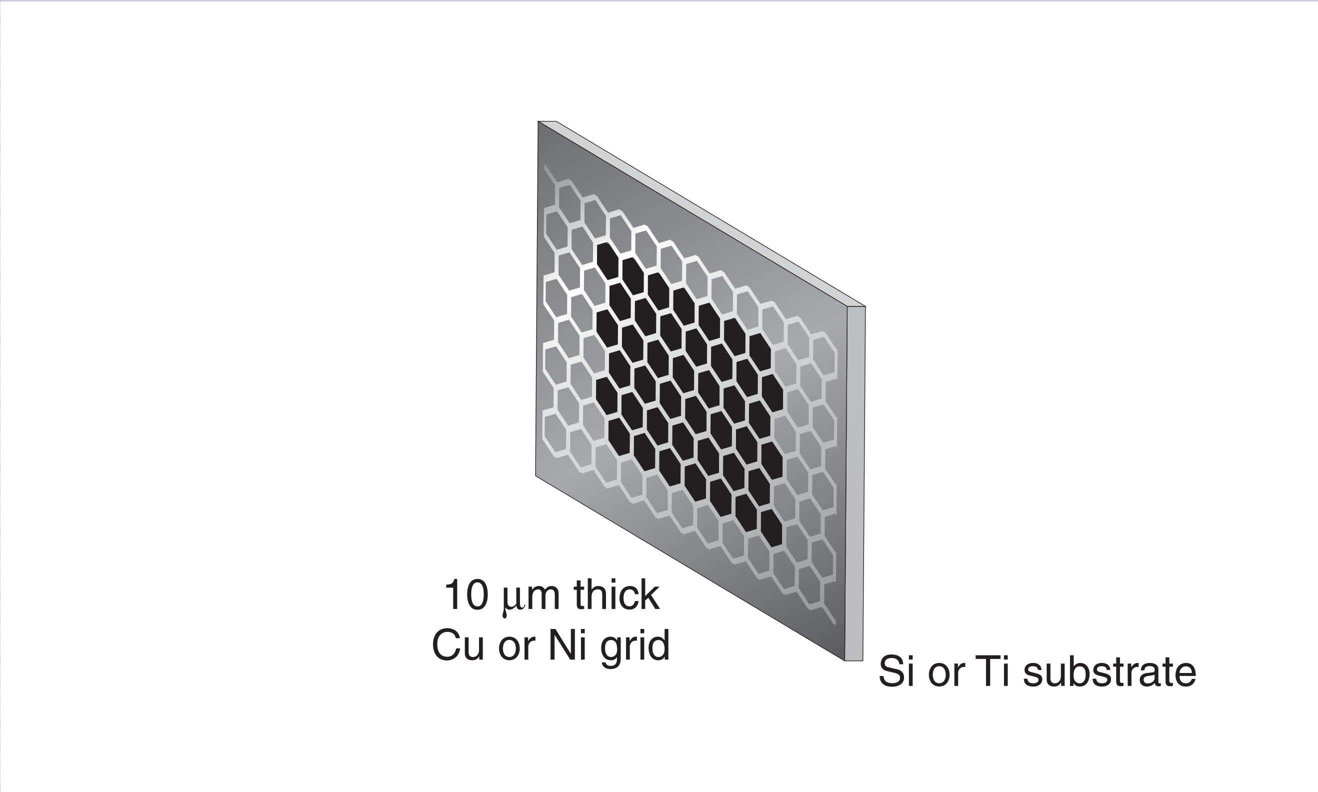
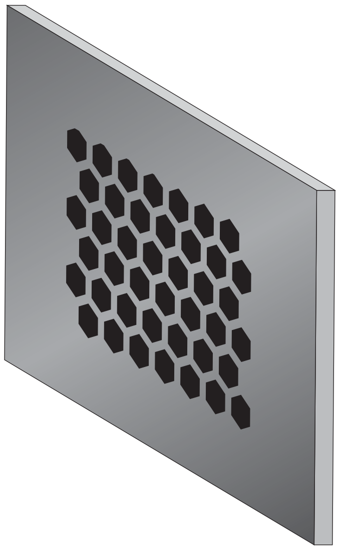
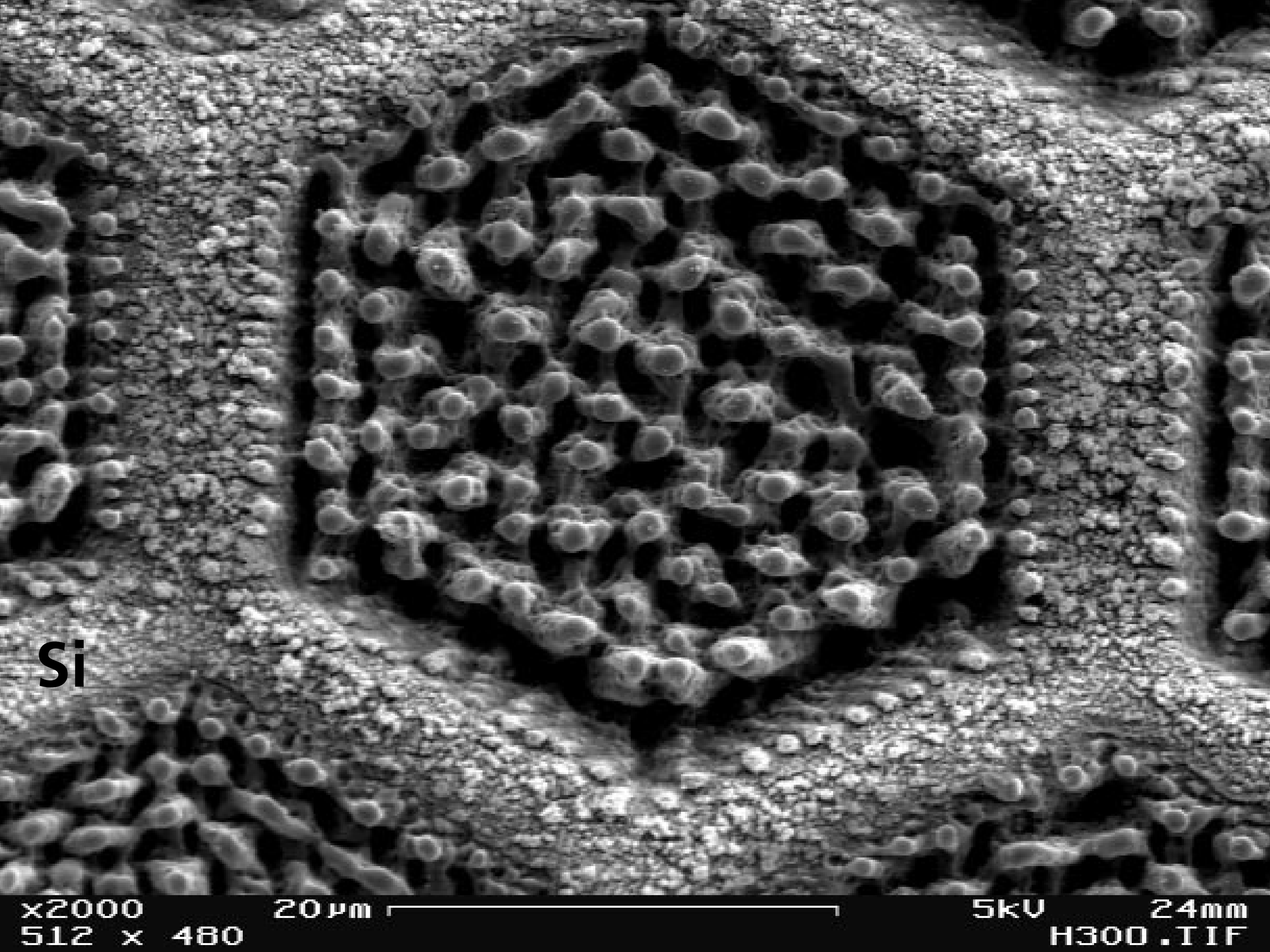
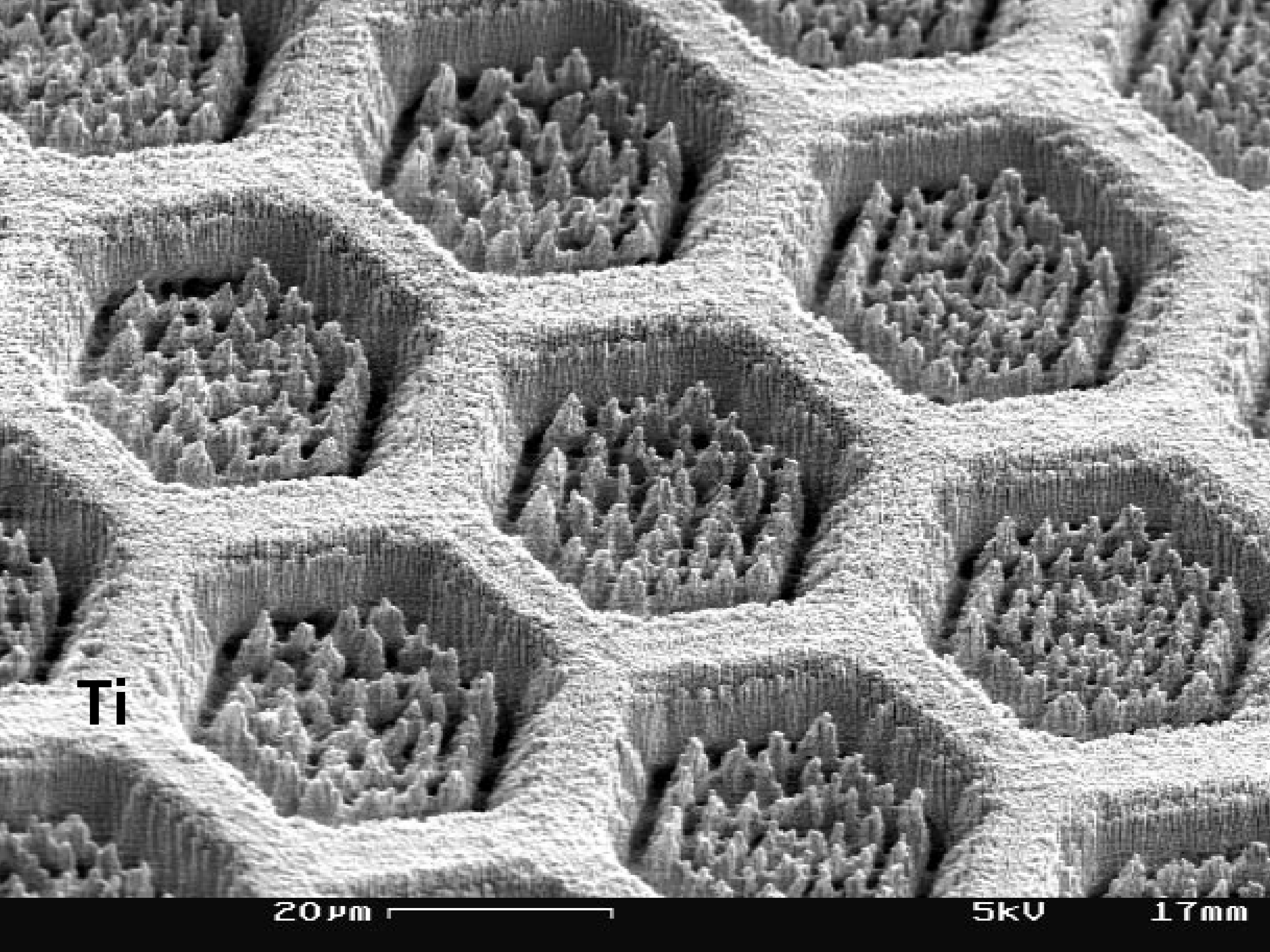


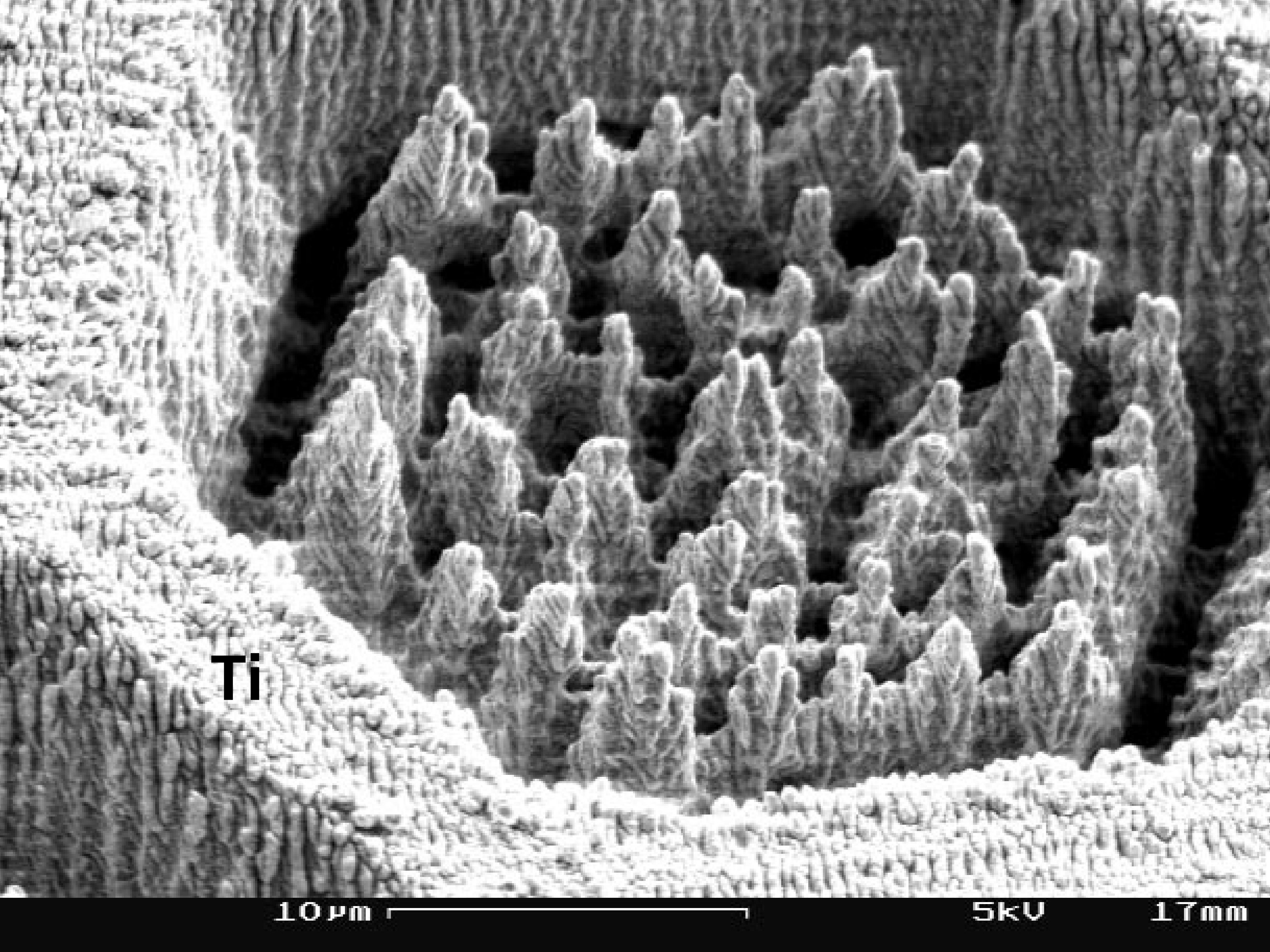
Outlook

remove grid




Si
x2000
20µm
5kV
24mm
512 x 480
H300.TIF


Ti
20μm
5kV
17mm


Ti
10μm
5kV
17mm

Outlook

Summary

Microstructured silicon

- fabricated by simple, maskless process

Summary

Microstructured silicon

- **fabricated by simple, maskless process**
- **can be integrated with microelectronics**

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Microstructured silicon

- **fabricated by simple, maskless process**
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- **generates IR photocurrent**

Summary

Microstructured silicon

- **fabricated by simple, maskless process**
- **can be integrated with microelectronics**
- **generates IR photocurrent**
- **provides stable, high field emission current**

Summary

Microstructured silicon

- fabricated by simple, maskless process
- can be integrated with microelectronics
- generates IR photocurrent
- provides stable, high field emission current
- is durable


GORDON McKAY
LABORATORY OF
APPLIED SCIENCE

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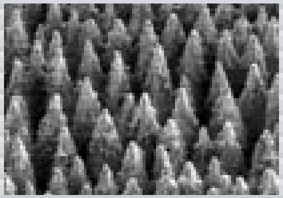
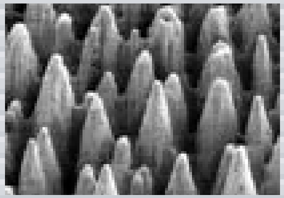
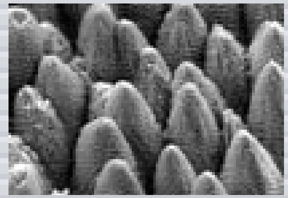
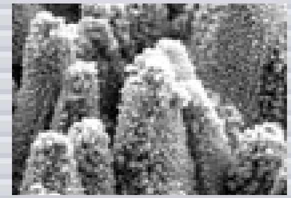
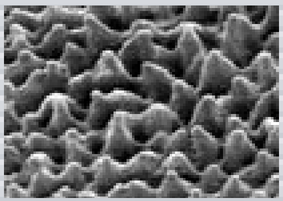
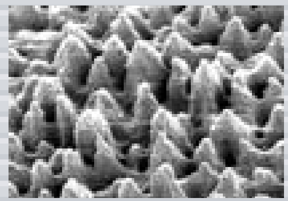
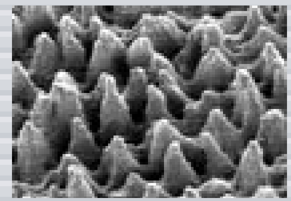
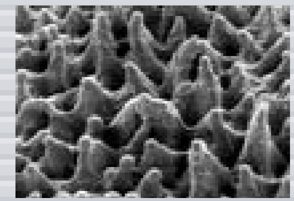
Dr. John Chervinsky (Harvard University)
Prof. Cynthia Friend (Harvard University)
Prof. Mike Aziz (Harvard University)

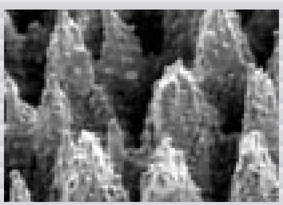
For a copy of this talk and
additional information, see:

http://mazur-www.harvard.edu

Materials

	SF_6	Cl_2	N_2	air	vacuum
Si					
Ti		reacts			

Only in SF_6:



Ge

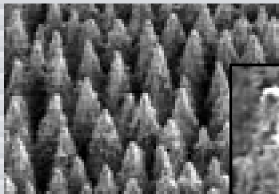
InP

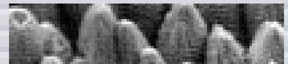
No spikes in SF_6: Ag, Al, Cu, Pd, Pt, Rh, Ta and GaAs

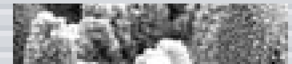
Materials

SF_6 | Cl_2 | N_2 | air | vacuum

Si







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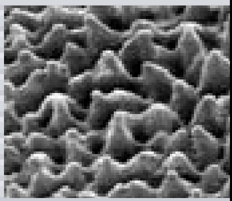
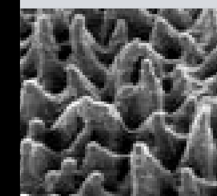
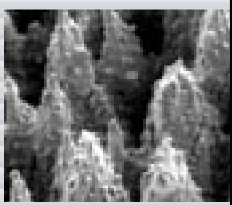




Only in SF



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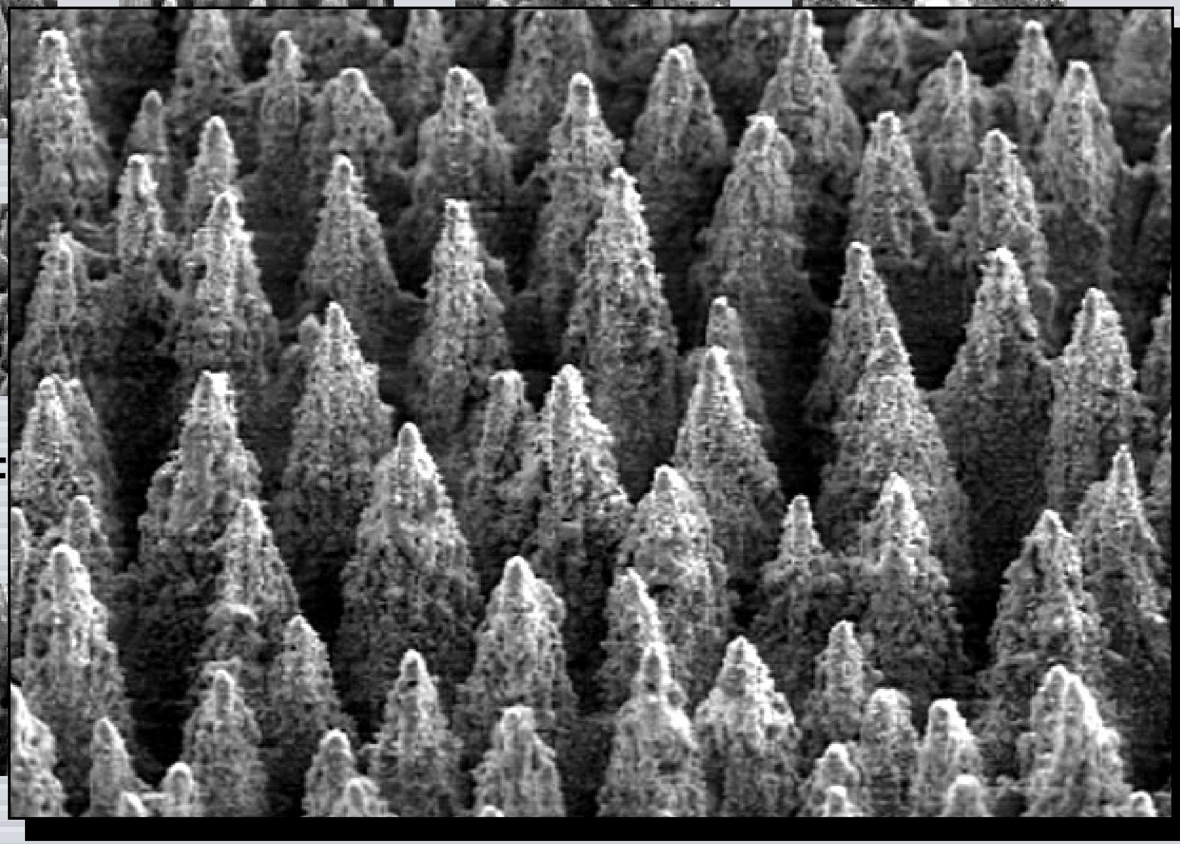
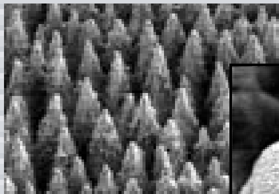
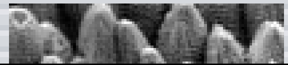
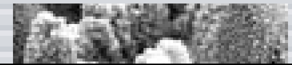
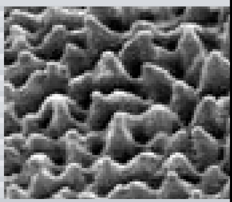
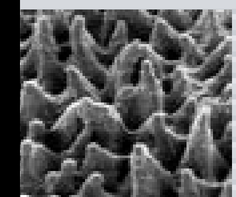


No spikes in SF_6: Ag, Al, Cu, Pd, Pt, Rh, Ta and GaAs

Materials

	SF_6	Cl_2	N_2	air	vacuum
Si					
Ti					

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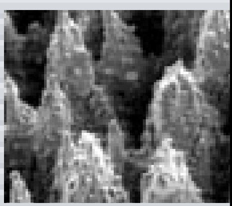

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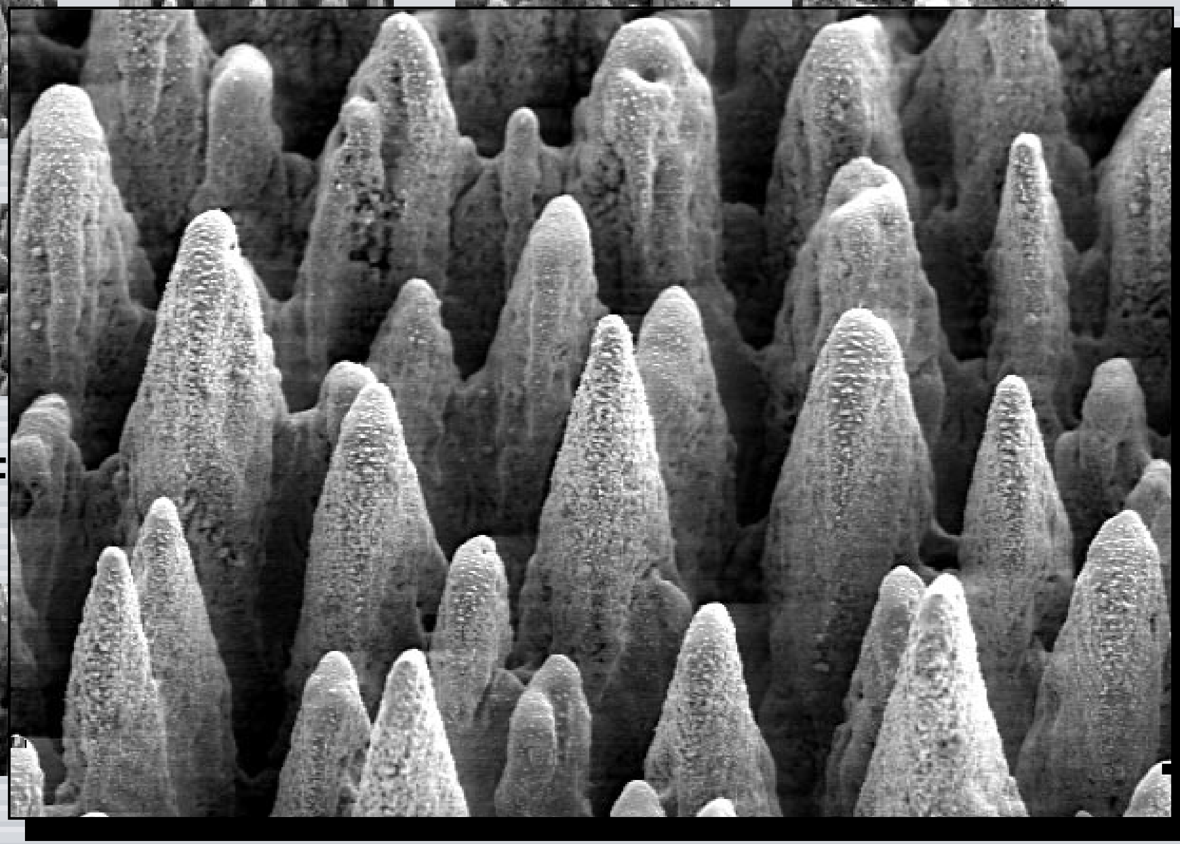
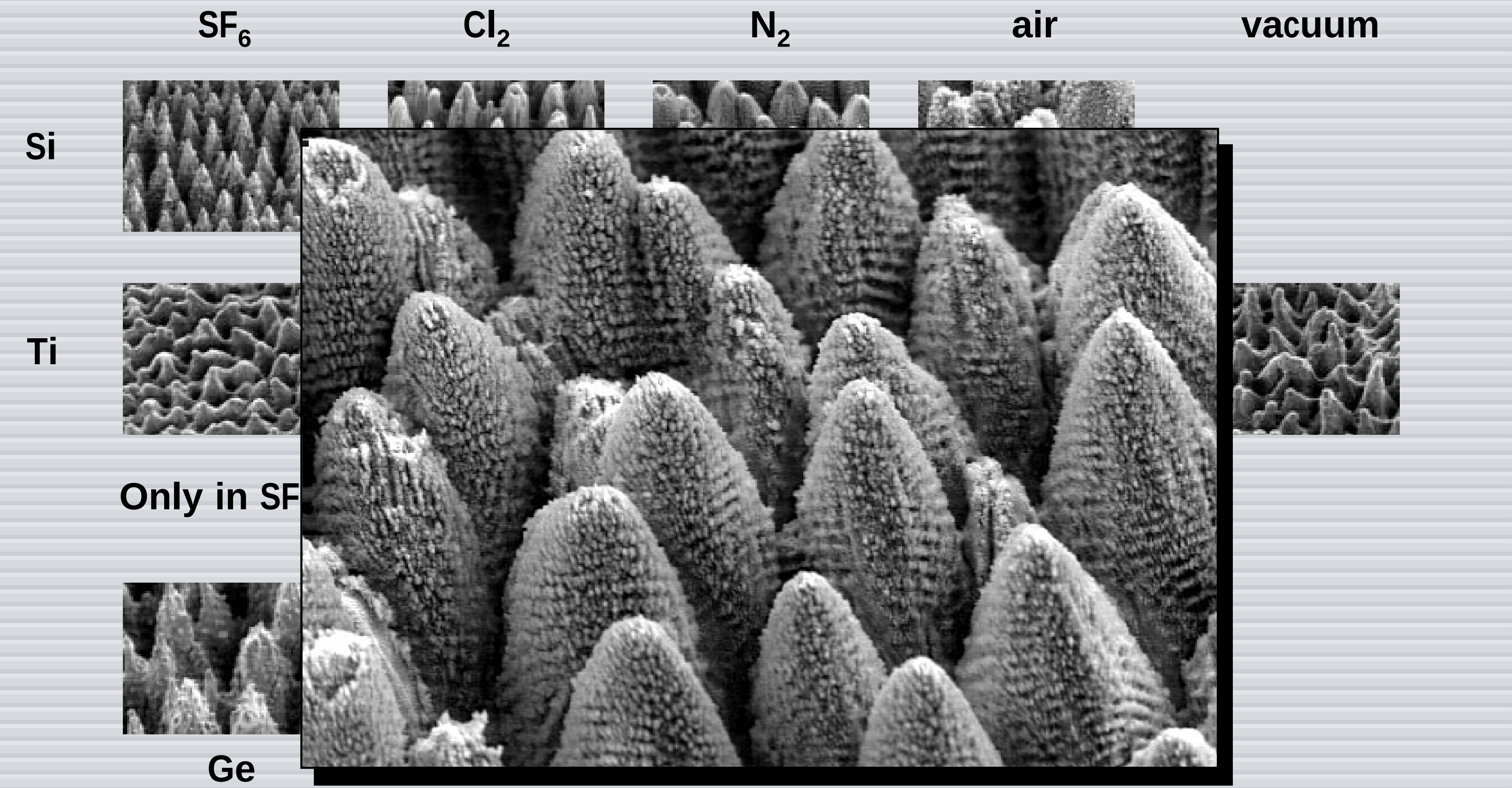


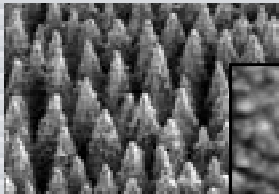
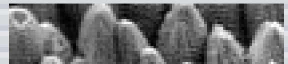
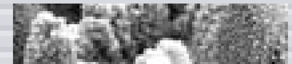
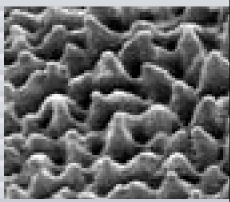
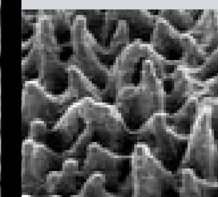
No spikes in SF_6: Ag, Al, Cu, Pd, Pt, Rh, Ta and GaAs

Materials



No spikes in SF_6: Ag, Al, Cu, Pd, Pt, Rh, Ta and GaAs

Materials

	SF_6	Cl_2	N_2	air	vacuum
Si					
Ti					

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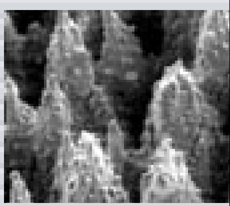

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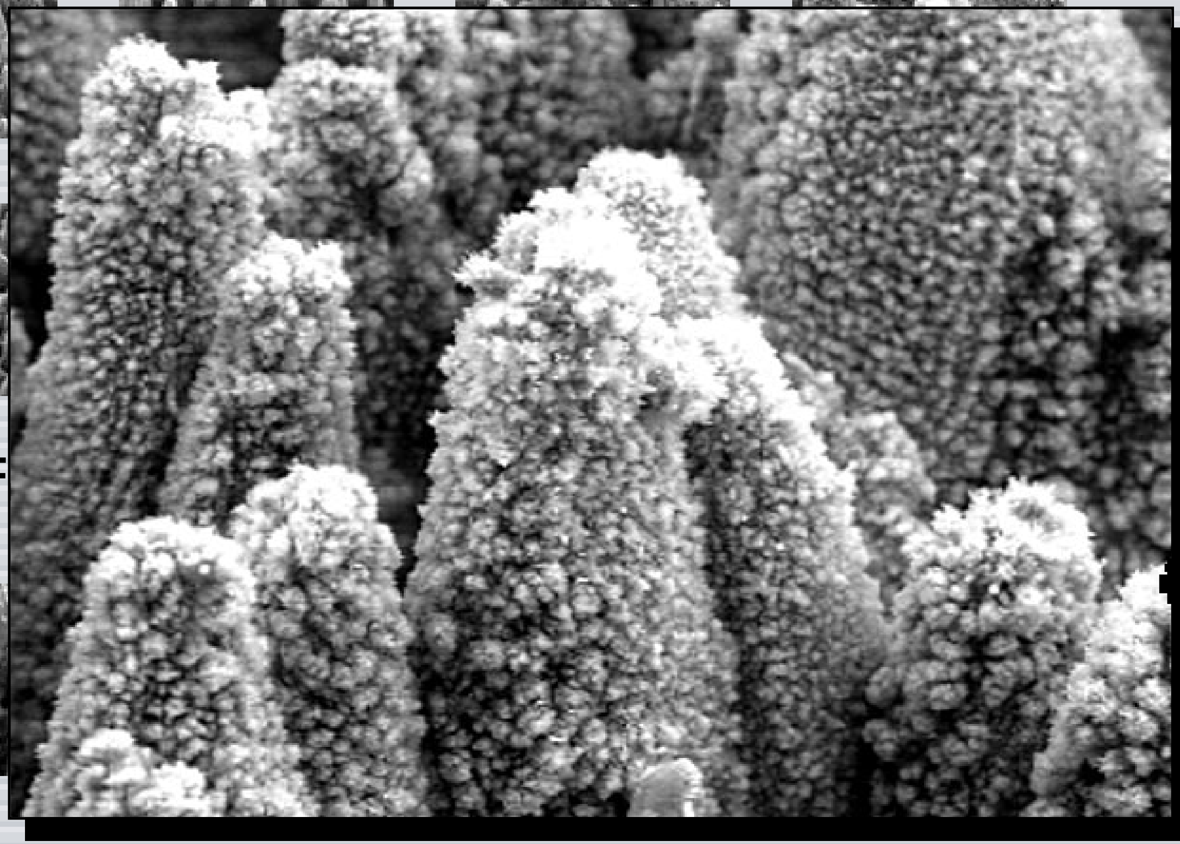

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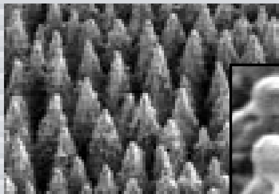
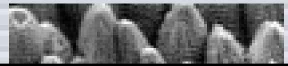
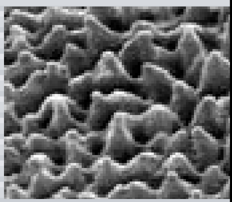
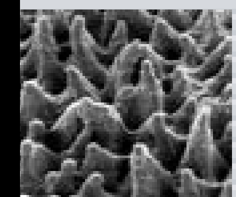
No spikes in SF_6: Ag, Al, Cu, Pd, Pt, Rh, Ta and GaAs

Materials

	SF_6	Cl_2	N_2	air	vacuum
Si					
Ti					

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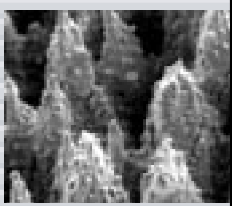

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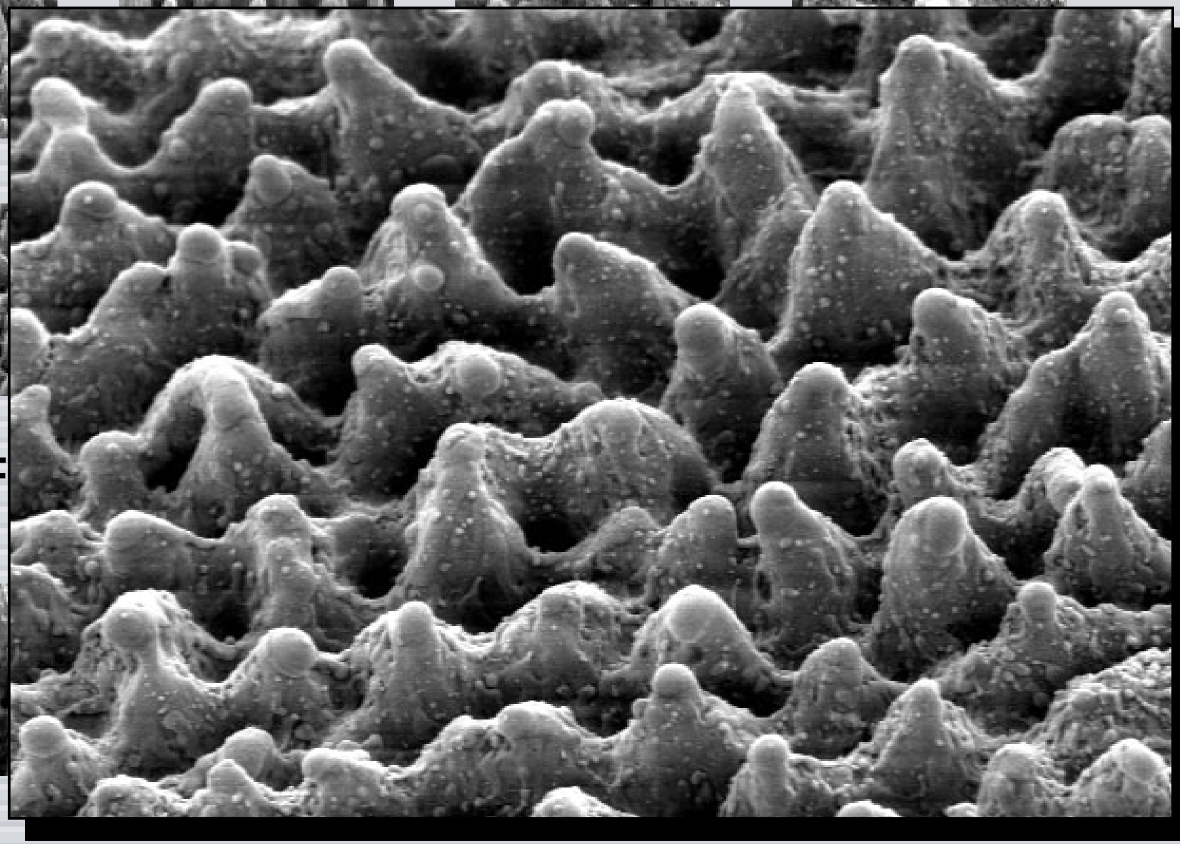


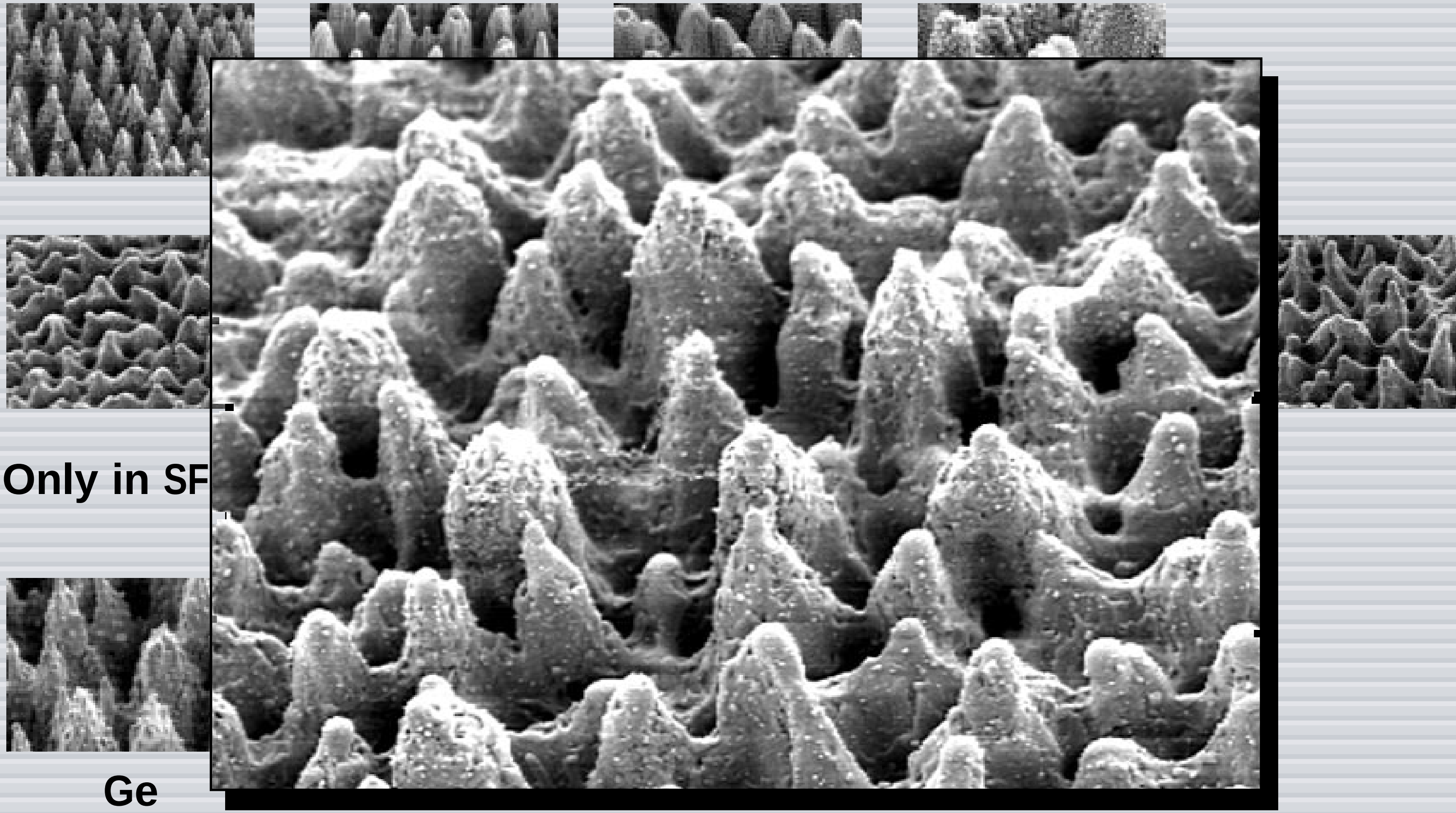
No spikes in SF_6:   Ag, Al, Cu, Pd, Pt, Rh, Ta and GaAs

Materials

SF_6 | Cl_2 | N_2 | air | vacuum

Si

Ti



Only in SF

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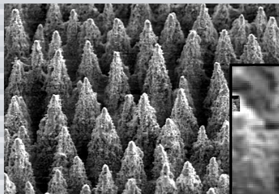
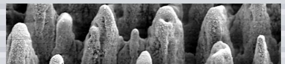
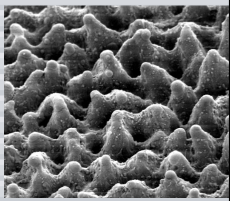
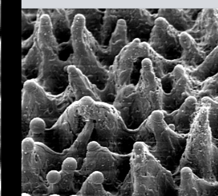
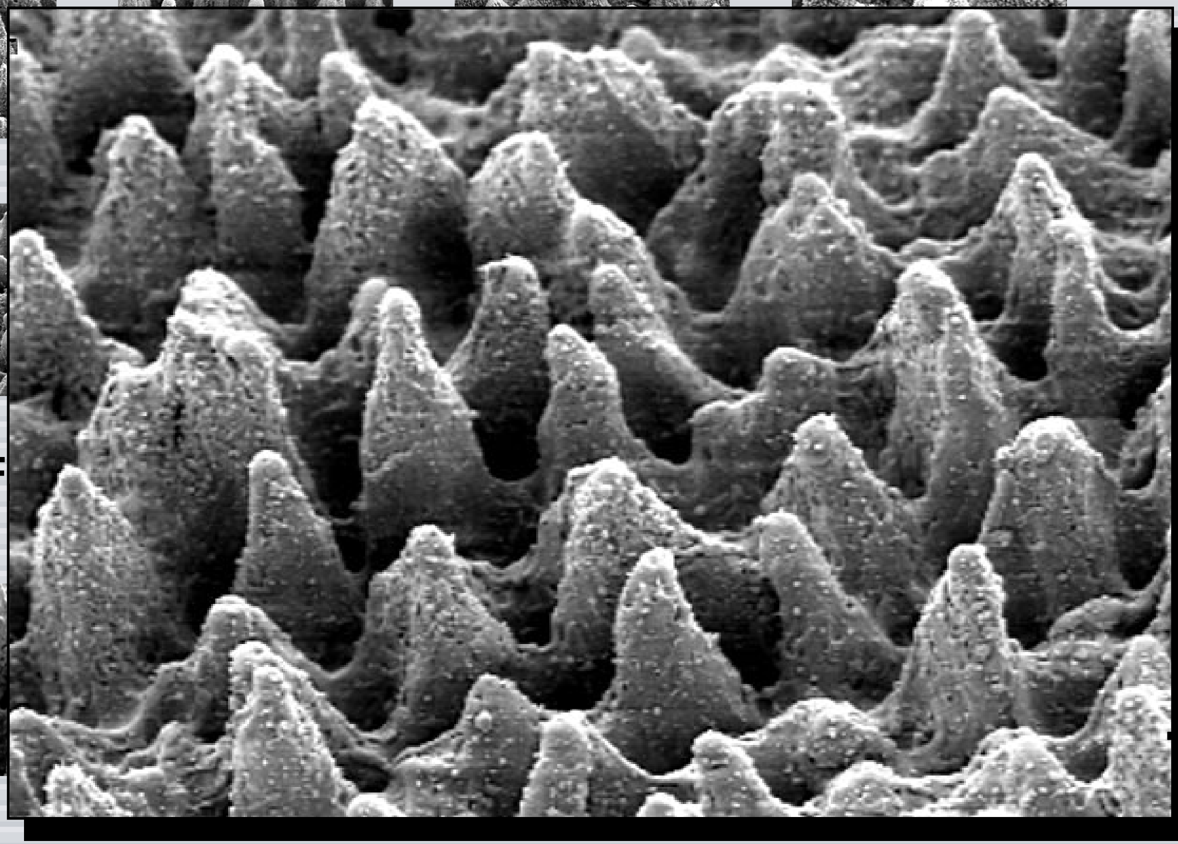
Materials

	SF_6	Cl_2	N_2	air	vacuum
Si					
Ti					



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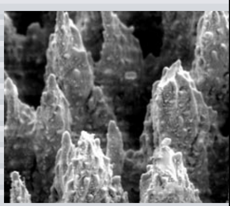

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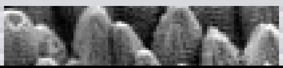
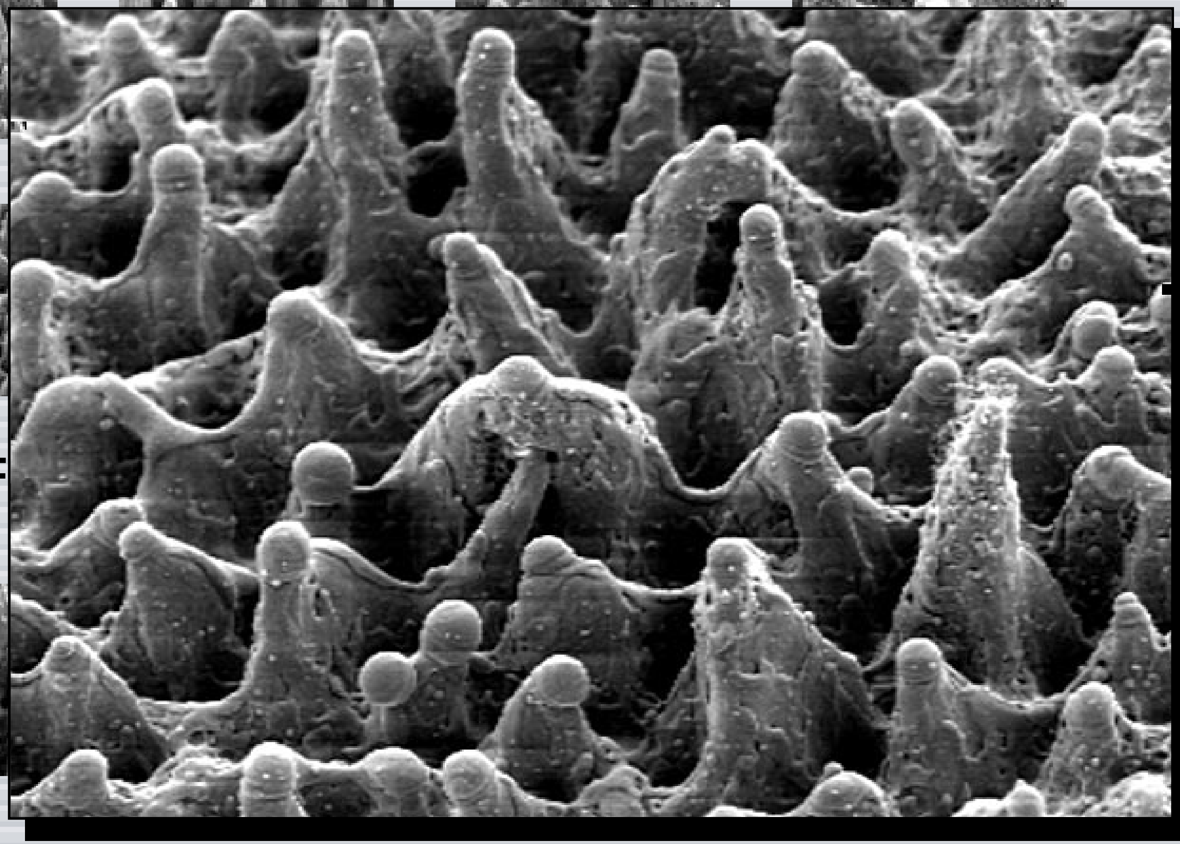
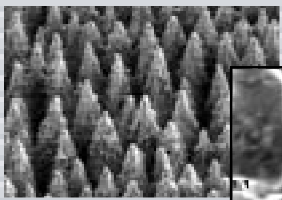
Materials

	SF_6	Cl_2	N_2	air	vacuum


Si





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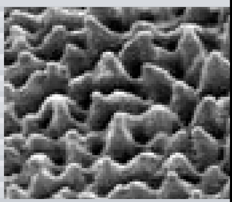

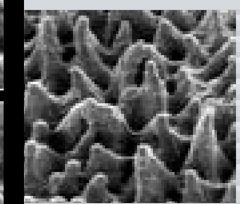

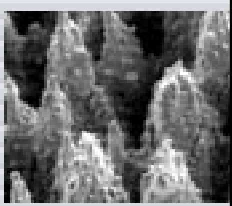

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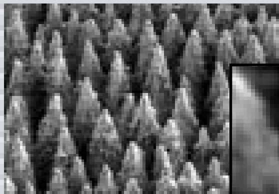
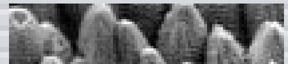
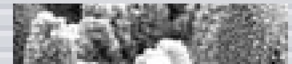
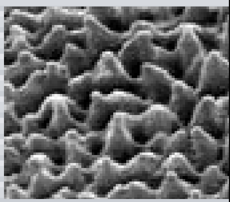
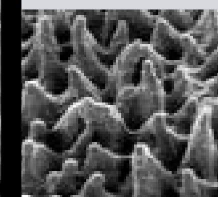
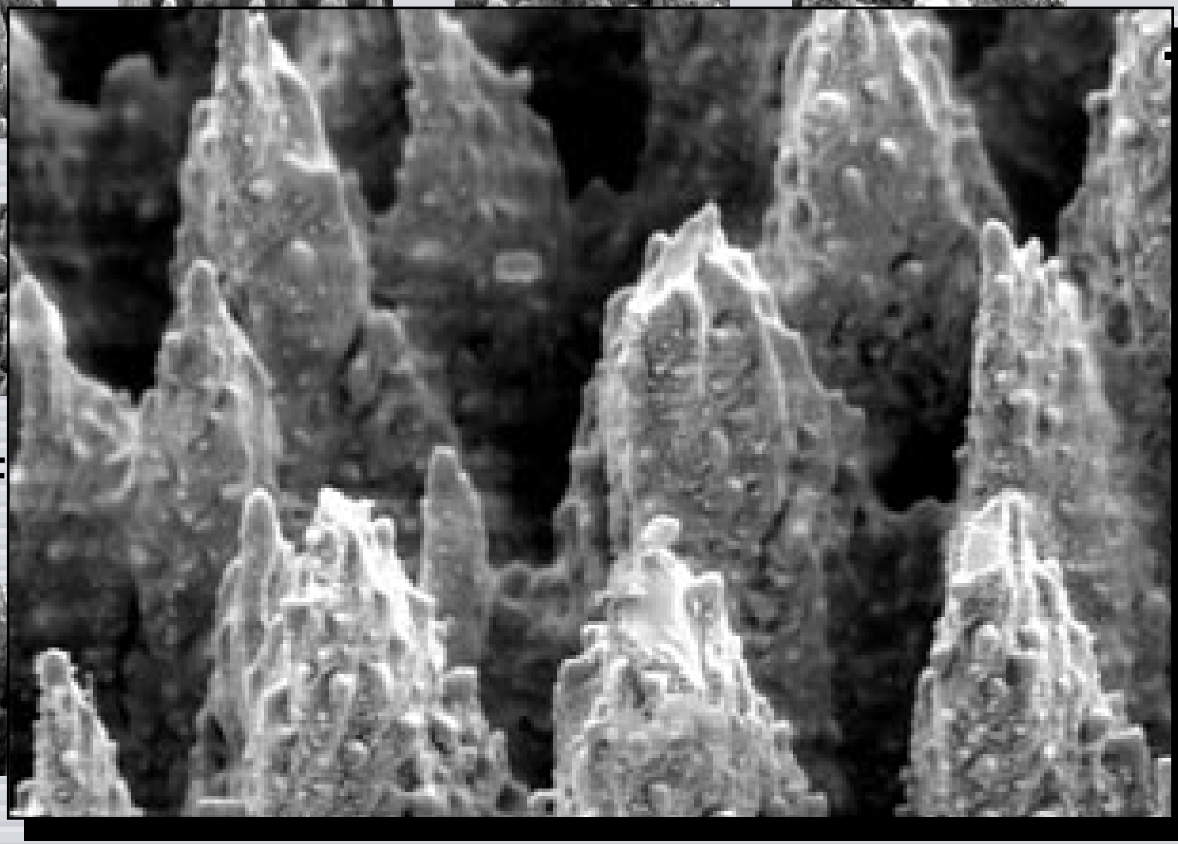
Materials

	SF_6	Cl_2	N_2	air	vacuum
Si					
Ti					



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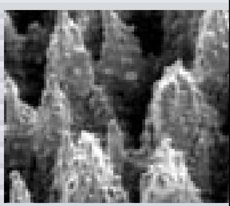

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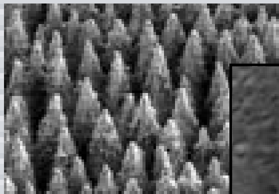

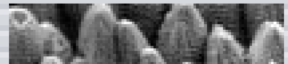

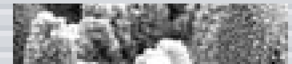

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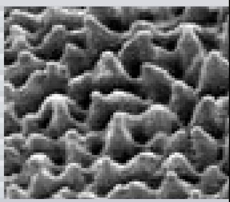

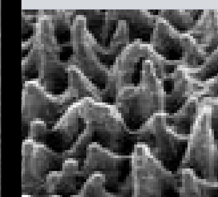

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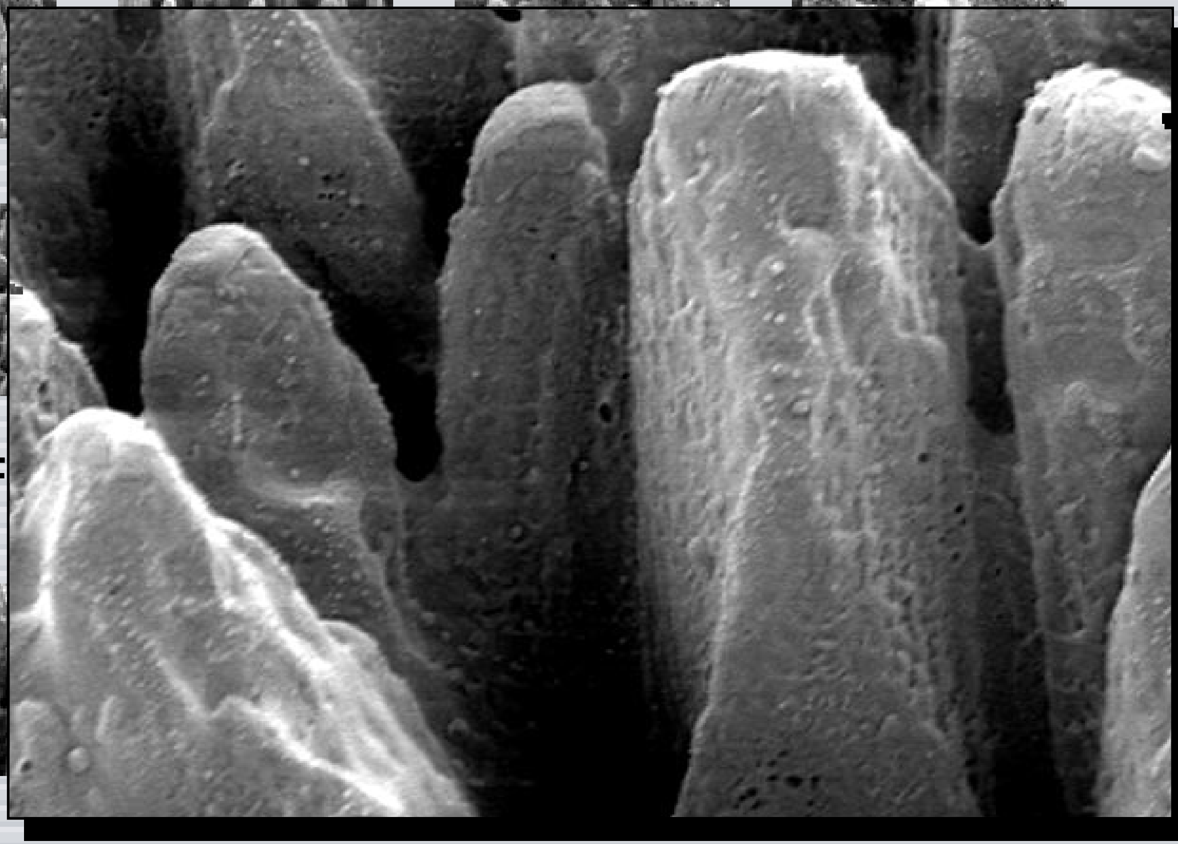

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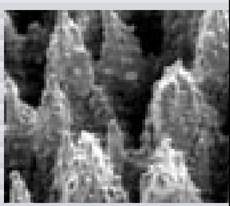

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