Femtosecond laser-structured silicon: properties and structure

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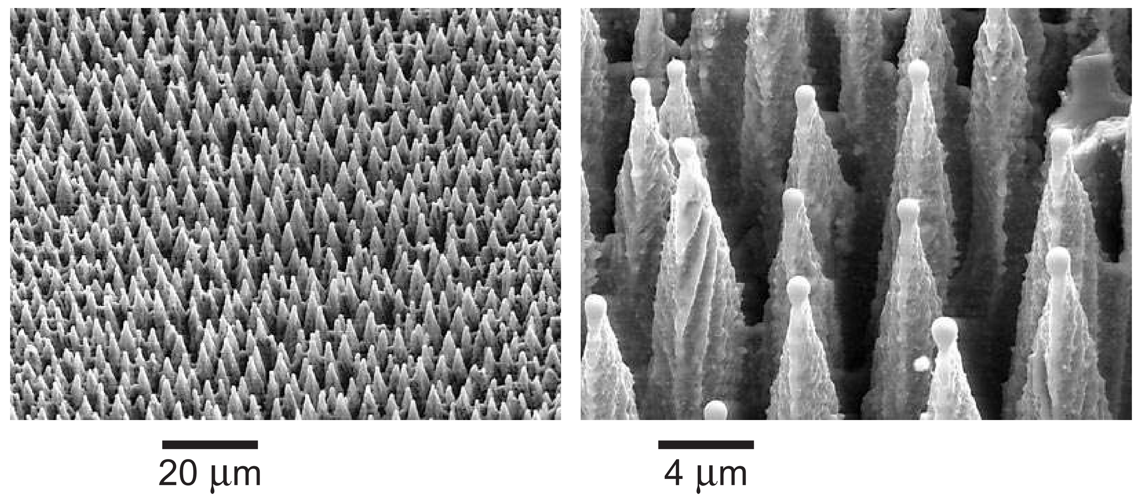
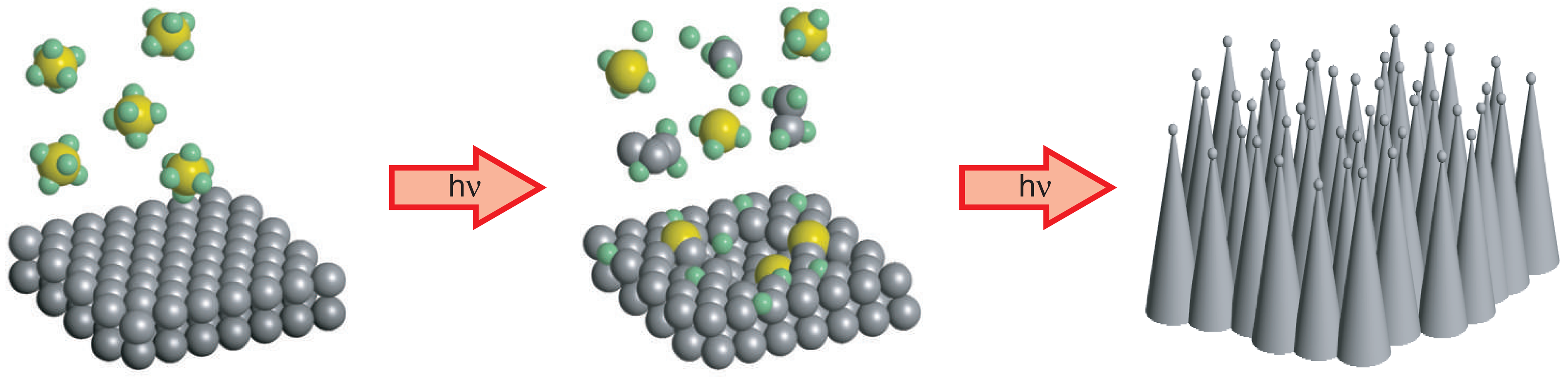
Introduction

We create sharp conical microstructures in silicon by irradiating Si(111) surfaces with a train of 100-fs laser pulses in the presence of SF_6.

Microstructured surfaces display near-unity optical absorption even at wavelengths below the band gap of silicon. The microstructures also exhibit high, stable field emission and visible photoluminescence.

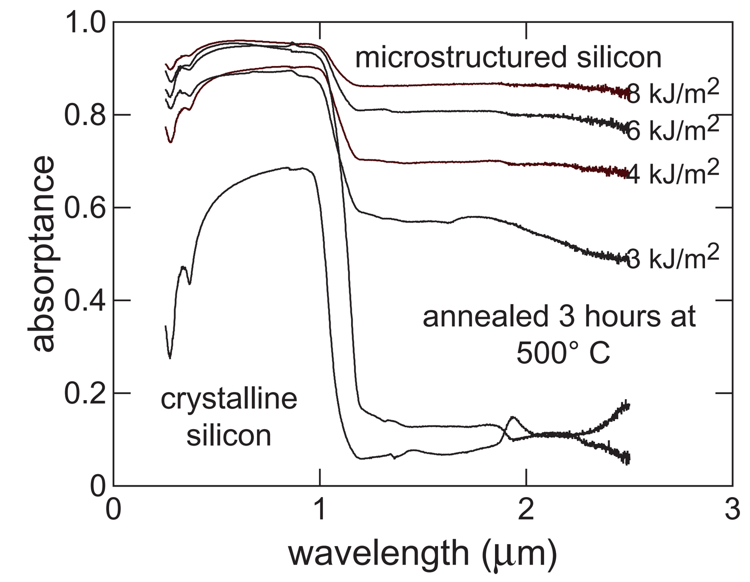


Structure formation involves an interplay between surface chemistry and optical excitation of both the surface and the ambient gas. Upon irradiation, volatile compounds of silicon and fluorine form on the substrate surface. Removal of these compounds etches the surface.

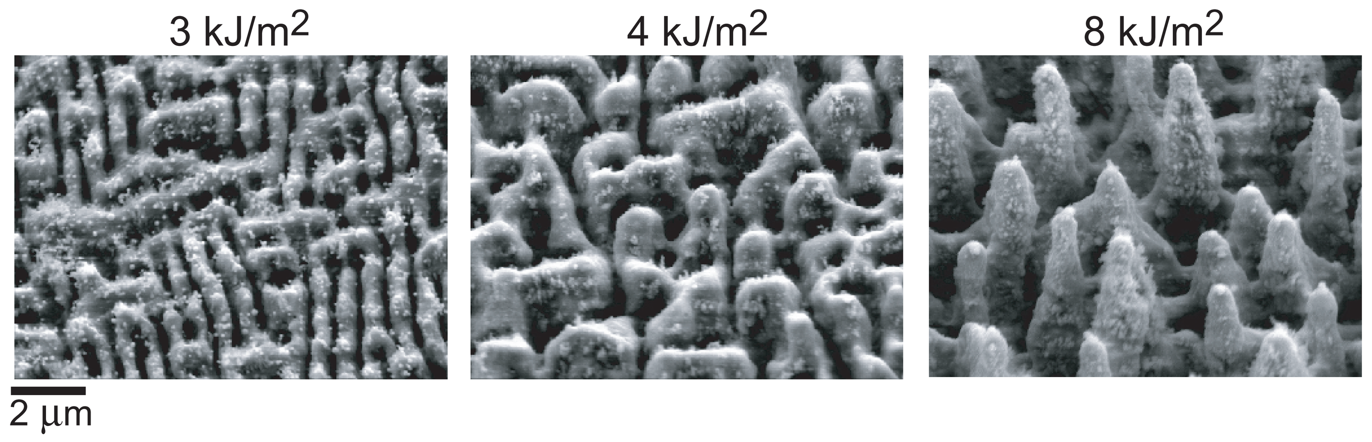


Below-band gap absorption

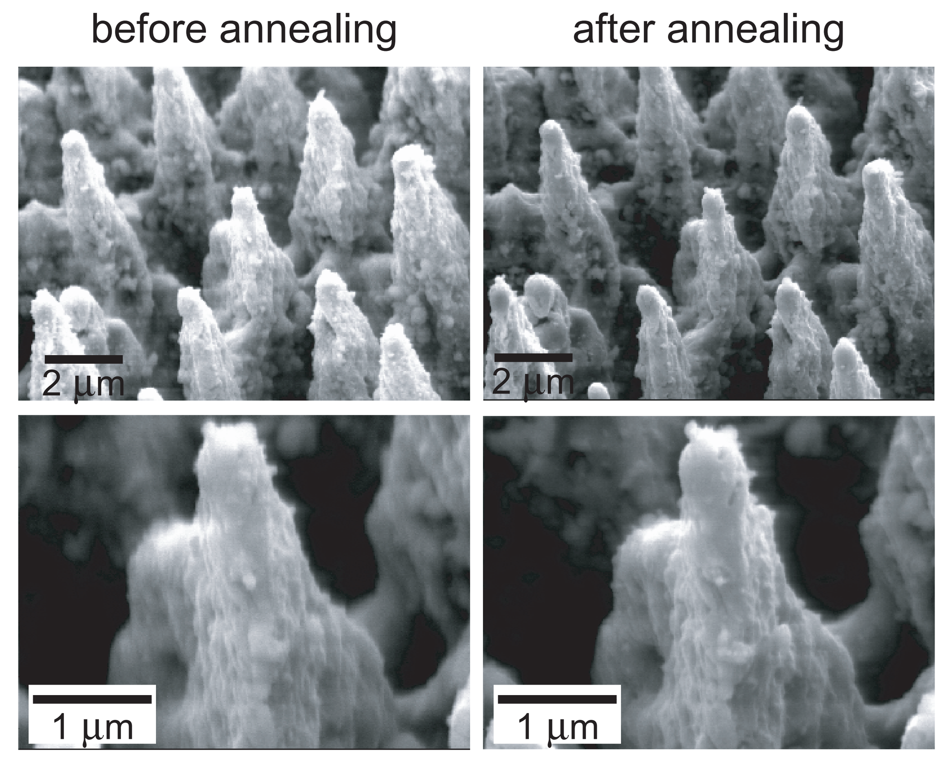
Microstructures formed in SF_6 show dramatically increased absorption of light from 250 to 2500 nm. Because ordinary silicon is transparent to light of energy below the band gap (λ > 1100 nm), absorption of these wavelengths is particularly remarkable.



Microstructure height depends on processing parameters, and increases with laser fluence, number of laser pulses, and background gas pressure. Absorption is highest for the tallest microstructures, but it is significant even for shallow, ridgelike microstructures.



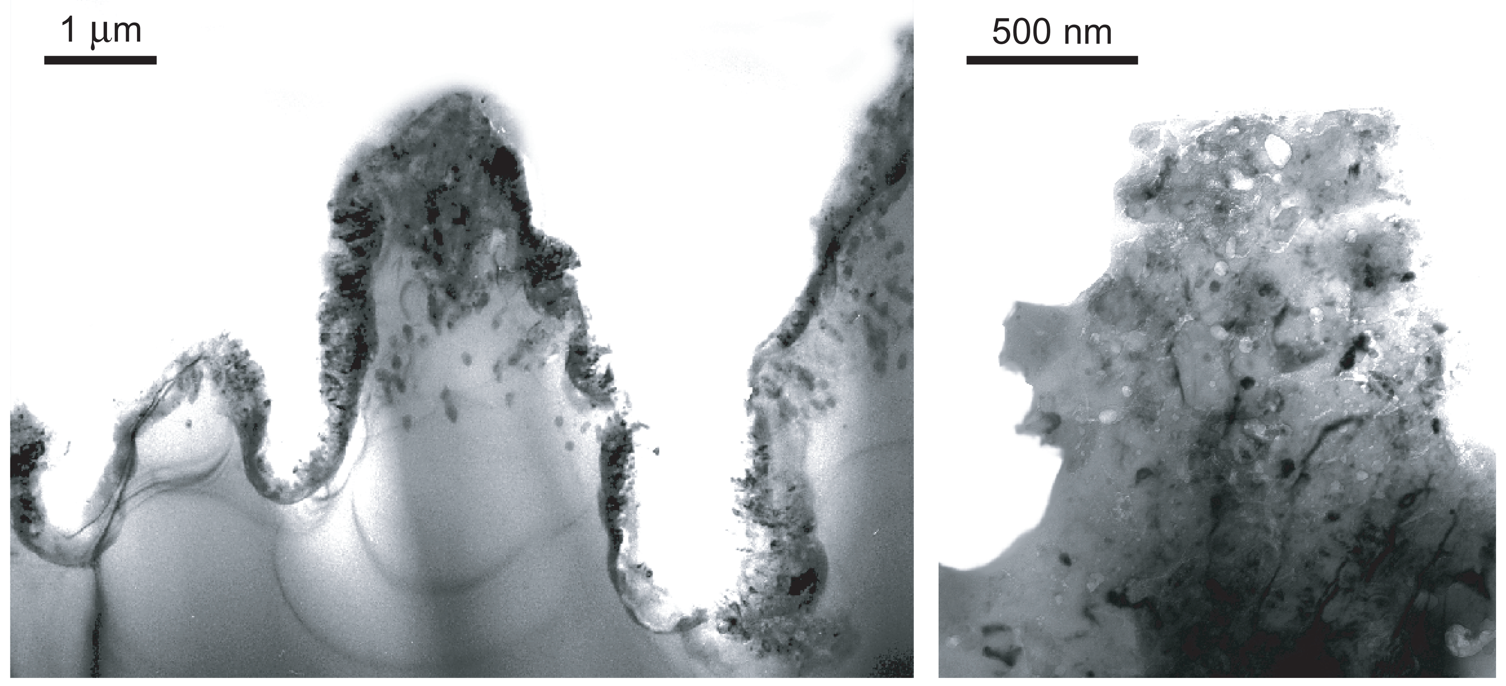
Annealing at 800 K for 3 hours nearly eliminates the below-band gap absorptance without changing microstructure morphology, and reduces the fluorine and sulfur content of the material.



Impurities (sulfur and fluorine), defects, and/or nanoparticles within the disordered surface layer are most likely responsible for the below-band gap absorption.

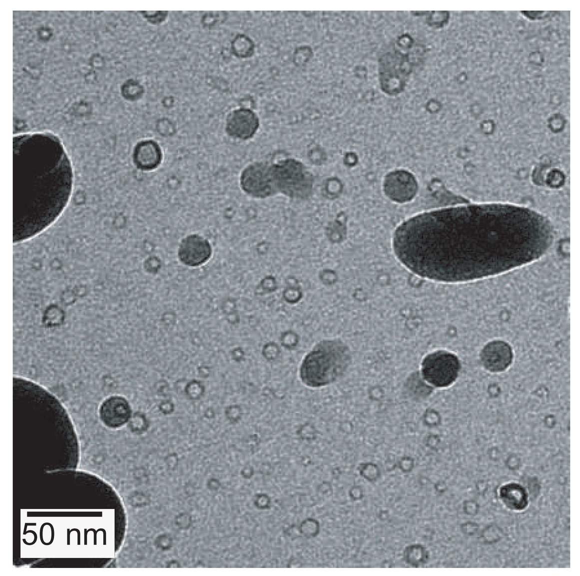
Surface nanocrystals

Cross-sectional transmission electron microscopy (TEM) of the microstructures reveals a core of crystalline silicon covered with a highly disordered layer including pores and nanocrystals.



Raman spectroscopy and photoluminescence confirm the presence of nanocrystals on the surface of the microstructures.

The ejected plume of ablated material includes silicon nanoparticles with a remarkably wide size range (5–50 nm). Some nanoparticles are most likely redeposited on the substrate as the microstructures form.

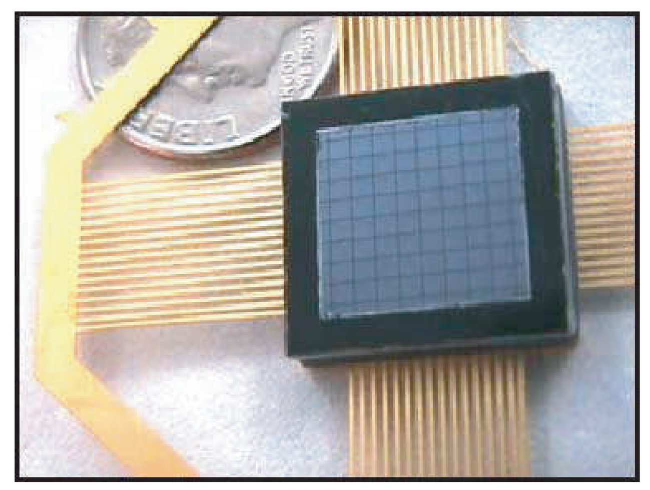


Secondary ion mass spectrometry (SIMS) and energy dispersive X-ray spectroscopy (EDX) indicate that the surface layer is oxidized silicon with a high concentration of sulfur and fluorine impurities.

Applications

Microstructured silicon holds promise for use in detectors, sensors, and photovoltaics.

Avalanche photodiodes (APDs) with a microstructured light collection area have more than twice the quantum efficiency of ordinary APDs at λ = 1064 nm and 1300 nm. Microstructuring could also extend the wavelength range of ordinary silicon photodiodes.


courtesy of Arieh Karger, RMD Inc.

Chemical functionalization of the surface (*e.g.*, SiC formation) could further improve properties for chemical sensors and optoelectronics.

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