

Nanocones as antireflection coating

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Reflection can be greatly reduced by graded refractive-index layers fabricated in a simple, scalable process.

When light hits the interface between media characterized by different refractive indices, a fraction is reflected: see Figure 1(a). This imposes severe limits on many optoelectronic devices such as solar cells¹ and LEDs.²

A range of techniques to reduce reflection have been proposed and developed. For example, a quarter-wavelength transparent layer is typically used as an antireflection coating in solar cells. However, this technique only works for specific wavelengths. Since solar energy covers a wide range of wavelengths, a broadband method is favored. With graded refractive-index layers, light only experiences a gradual change of the refractive index instead of hitting a sharp interface—see Figure 1(c)—and reflection can be greatly reduced for a large range of wavelengths and angles of incidence. Several techniques have been developed to fabricate these layers.^{3,4} However, many involve complicated processes or work only for certain materials.

We have developed a simple, low-temperature, integrated-circuit-compatible fabrication process. To date, it has thus far only been demonstrated on crystalline⁵ and hydrogenated amorphous silicon (a-Si:H),⁶ but it can in principle be applied to other materials as well. A monolayer of silica nanoparticles is first formed on the surface of a sample with an amorphous-silicon thin film on top: see Figures 1(d) and 1(e). The sample is then placed into the reactive-ion etcher (RIE), with the nanoparticles serving as a mask for etching. Either nanowire or nanocone arrays—Figures 1(f) and 1(g), respectively—can be obtained, depending on etching conditions.

We used three samples to evaluate the antireflection effect (see Figure 2). A 1 μm -thick a-Si:H thin film was deposited onto each, while a monolayer of silica nanoparticles was preformed on the second and third samples. After RIE etching, nanowire and nanocone arrays were formed on the second and third samples, respectively. The thin-film sample had a highly reflective,

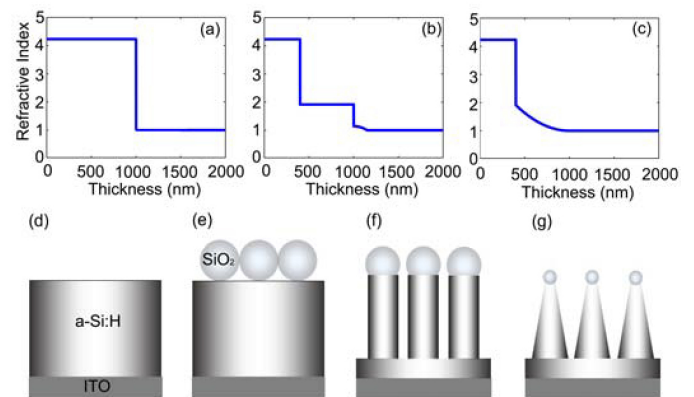


Figure 1. Effective refractive-index profiles of the interface between air and (a) hydrogenated amorphous-silicon (a-Si:H) thin film, (b) 600nm a-Si:H nanowire (NW) arrays, and (c) 600nm a-Si:H nanocone (NC) arrays. (d)–(g) Schematic illustrations of 1 μm -thick a-Si:H on indium tin oxide (ITO)-coated glass substrate, a monolayer of silica (SiO_2) nanoparticles on top of a-Si:H thin film, and arrays of NWs and NCs.

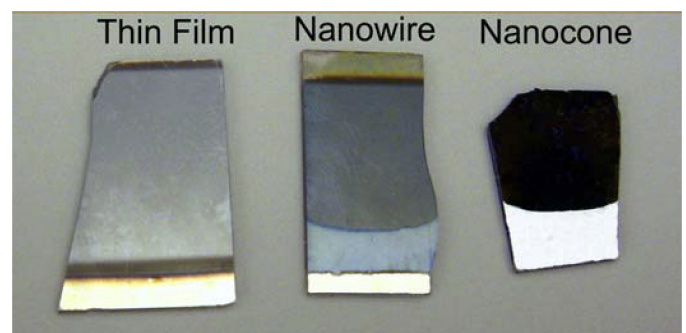


Figure 2. (left) a-Si:H thin film, (middle) NW arrays, and (right) NC arrays.

mirrorlike surface. The sample with nanowire arrays reflected less light, while the sample with nanocone arrays looked darkest, exhibiting enhanced absorption because of suppression of

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reflection from the front surface. These results demonstrate that absorption is greatly enhanced with nanocone arrays.

We obtained absolute hemispherical measurements to quantitatively characterize our samples. Their total absorption at a wavelength $\lambda = 488\text{nm}$ is shown in Figure 3(a) for different angles of incidence. The sample with nanocone arrays demonstrated the highest absorption, i.e., 98.4% around normal incidence, which offers a significant advantage over both nanowires (85%) and thin films (75%). The performance of the nanocone sample also showed a reduced dependence on the angle of incidence and significantly higher absorption at any angle. At angles of incidence up to 60° , the total absorption was maintained above 90%, which compares favorably with 70 and 45% for the nanowire arrays and thin film, respectively. We also measured the absorption over a wide range of wavelengths (400–800nm), covering most of the useful spectral regime for a-Si:H solar cells: see Figure 3(b). Between 400 and 650nm, nanocone-array absorption was maintained above 93%, which was much better than for both the NW arrays (75%) and thin film (64%). The measured total absorption decreased to 88% at 700nm—corresponding to the a-Si:H band gap (1.75eV)—which is also better than for either nanowires (70%) or thin film (53%).

In summary, we developed a scalable and integrated-circuit-compatible process to fabricate nanocone arrays on amorphous-silicon thin film. We proved that nanocone arrays provide excellent impedance matching of a-Si:H and air through a gradual reduction of the effective refractive index with distance from the surface. They, therefore, exhibit enhanced absorption because of superior antireflection properties over a large range of wavelengths and angles of incidence. We are currently developing solar-cell devices based on these nanocone arrays.

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Jia Zhu is a PhD student. His work focuses on nanomaterials for solar-cell applications.

Yi Cui received a bachelor's degree in chemistry from the University of Science and Technology of China in 1998. He worked on his PhD at Harvard University from 1998 to 2002, supervised by Charles Lieber. His PhD thesis concerned semiconductor nanowires for nanotechnology including synthesis, nanoelectronics, and nanosensor applications. He was subsequently

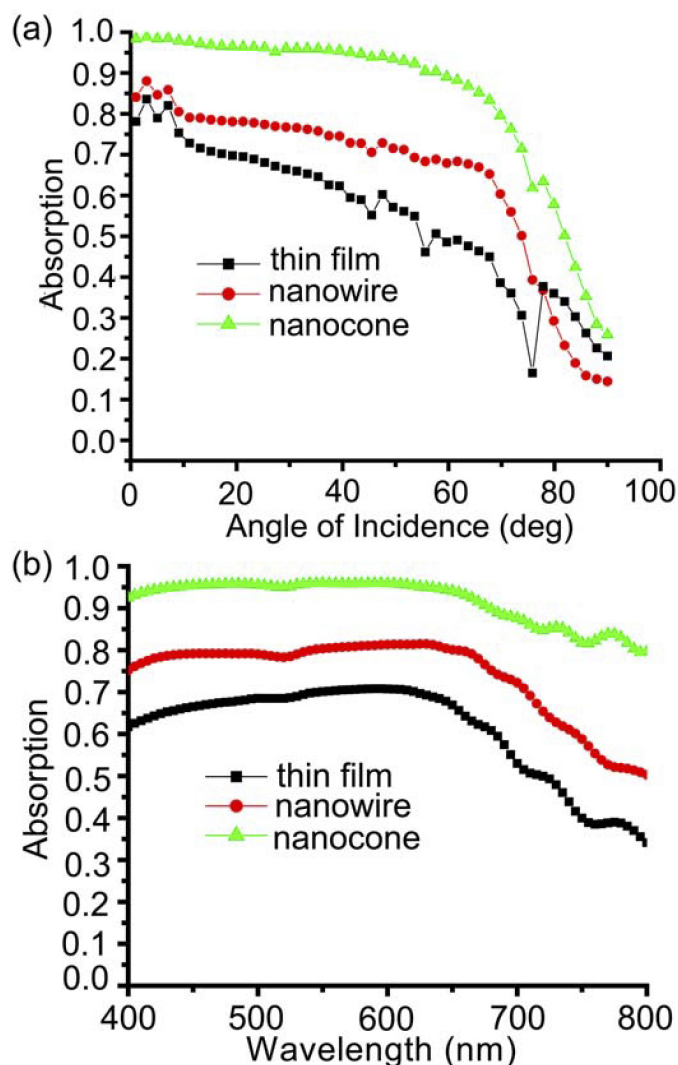


Figure 3. Absorption measurements of samples with a-Si:H thin film, NW arrays, and NC arrays as top layer (a) for different angles of incidence (at a wavelength $\lambda = 488\text{nm}$) and (b) over a large range of wavelengths at normal incidence.

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