Nanostructured Photon Management for High Performance Solar Cells

Yi Cui
Department of Material Science and Engineering, Stanford University, Stanford, CA 94305
E-mail: yicui@stanford.edu

Abstract- **Advanced photon management, involving both absorption enhancement and reflection reduction, is critical to all the photovoltaic devices. Here we discuss a novel solar cell structure with an efficient photon management design. The centerpiece of the design is the nanocone structure, which is fabricated by a scalable low temperature process. With this design, devices with very thin active layer can achieve near perfect absorption because of both efficient antireflection and absorption enhancement over a broad band of spectra and a wide range of angles of incidence. The device performance of this design is significantly better compared to conventional devices. More excitingly, the design and process is in principle not limited to any specific materials, hence it opens up exciting opportunities for a variety kinds of photovoltaic devices, to further improve the performance, reduce materials usage, and relieve the abundance limitation.**

I. INTRODUCTION

Solar cells that covert solar power into electricity are one of the most important candidates of renewable energy. In spite of significant progress made in the past several decades, technology improvement to further improve the efficiency and reduce the cost is still necessary for photovoltaic devices to be economically competitive for large-scale applications. From that perspective, advanced photon management, which enabling efficient absorption within very thin film, is very desirable, since it will minimize optical and transport losses to improve the efficiency, and reduce material usages to reduce the cost. However, a broad-band coverage of solar spectrum makes efficient photon management extremely challenging. Most of designs so far work best only for a specific wavelength, or involve tradeoff between antireflection and absorption enhancement. Here we demonstrate a novel device structure design, based on nanocone arrays, which can achieve anti-reflection and absorption enhancement at the same time over a wide range of wavelength and angles of incidence. Solar cell devices based on this structure can achieve near perfect absorption within much thinner layers, and hence very high short-circuit current and overall efficiency. Hydrogenated amorphous Si (a-Si:H) solar cells are used here as an example to demonstrate the concept.

II. FABRICATION OF NANOWIRE AND NANOCONE ARRAYS

A large scale, low temperature, IC-compatible process is used to fabricate a-Si:H nanowire (NW) and nanocone (NC) arrays [1] [2].

Figure 1 shows the general fabrication process. Monodisperse SiO_2 nanoparticles, synthesized in-house, were assembled into a closepacked monolayer on top of a thin film layer using the Langmuir-Blodgett (LB) method. Monodisperse SiO_2 particles with diameters from 50 to 800 nm were produced by a modified Stöber synthesis. The diameter and spacing of the nanoparticles were tuned by selective and isotropic RIE of SiO_2. The etching is based on fluorine chemistry using a mixture of O_2 and CHF_3. Depending on specific etching condition, either Si NWs or NCs can be obtained by using Cl_2 based selective and anisotropic RIE [1]. The diameter and spacing of these nanostructures were determined by the initial nanoparticle sizes and both SiO_2 and Si etching times.

Fig. 1. Fabrication Process of Nanowires and Nanocones

III. ANTI-REFLECTION

As shown in Figure 2 (a), when light hits the interface between media characterized by different refractive indices, a significant fraction of it is reflected. A range of techniques to reduce reflection have been proposed and developed. For example, a quarter-wavelength transparent layer with an intermediate refractive index is typically used as an antireflection coating in solar cells (Figure 2(b)). However, this technique only works for specific wavelengths. Since solar energy covers a wide range of wavelengths, a broadband method is more favorable. In the nanocone case, with graded refractive-index layers, light only experiences a gradual change of the refractive index instead of hitting a sharp interface (see Figure 2(c)), and reflection can be greatly reduced for a large range of wavelengths and angles of incidence.

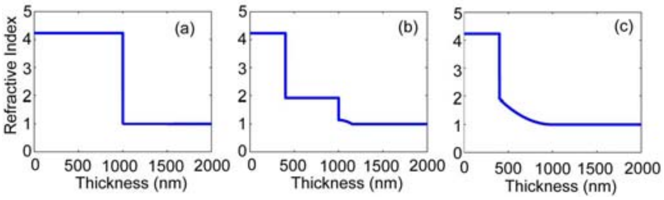

Fig. 2 The effective refractive index profiles of the interfaces between air and (a) a-Si:H thin film, (b) a-Si:H NW arrays, and (c) a-Si:H NC arrays.

Three samples were used to evaluate the antireflection effect (see Figure 3). A 1μm-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, mirrorlike surface (Figure 3 left). The sample with nanowire arrays reflected less light (Figure 3 middle), while the sample with nanocone arrays looked darkest (Figure 3 right), exhibiting enhanced absorption because of suppression of reflection from the front surface.

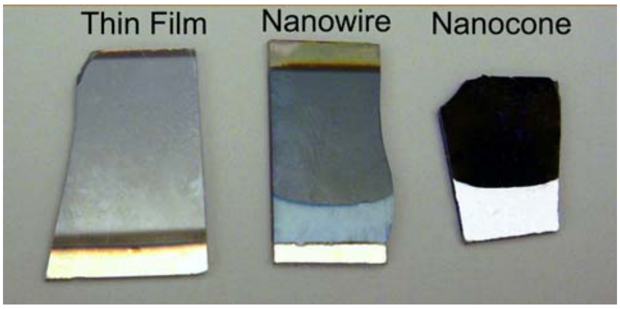

Figure 3. (left)a-Si:H thin film, (middle) NW arrays, and (right) NC arrays

Absolute hemispherical measurements using integrating sphere were used to quantitatively characterize these three samples. The absorption over a wide range of wavelengths (400–800nm) was measured. With the band-gap of a-Si:H around 1.75ev, this range covers most of the useful spectral regime for a-Si:H solar cells. 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%).

Their total absorption at a wavelength of 488nm is also measured 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.

IV. ABSORPTION ENHANCEMENT

More excitingly, these nanostructures can scatter light along the in-plane dimension, which enhance the light traveling path for absorption, providing a novel light trapping mechanism. Compared with the Lambertian scattering, which is based on well-understood surface texturing with features much larger than light wavelengths for efficient absorption enhancement effect, our devices uses subwavelength nanostructures, which are more feasible for solar cells with only sub-micrometer thick absorber layers.

In geometrical optic, where dimensions generally significantly larger than wavelengths, it is well know that absorption enhancement will be ultimately constrained by so called Yablonovitch limit [3]. However, for most of the new generation solar cell devices, the thickness of the active layers is typically only around 1-2μm or less, which is comparable to the wavelength of most of solar spectrum. Whether a similar limit exists in the wave optics regime is still an open question. These nanostructures with precise control of diameter and spacing down to tens of nanometers provides a powerful platform for the study of absorption enhancement limit in the wave optics regime.

V. SOLAR CELL PERFORMANCE

Combining both superior antireflection and efficient absorption enhancement, solar cell devices based on this novel photon management design can achieve near perfect light absorption with very thin active layers. Therefore, significant short-circuit current and efficiency improvement can be achieved compared to conventional devices.

REFERENCES

[1] Hsu, C.-M., Connor, S. T.,Tang, M.X. & Cui, Y. Wafer-Scale silicon nanopillars and nanocones by Langmuir-Blodgett assembly and etching. *Appl. Phys. Lett.* **93**, 133109 (2008).

[2] Zhu, J., Yu, Z., Burkhard, G. F., Hsu, C.-M., Connor, S. T., Xu, Y., Wang, Q., McGehee, M., Fan, S. & Cui, Y. Optical Absorption Enhancement in Amorphous Silicon Nanowire and Nanocone Arrays. *Nano Lett.* **9**, 279-282 (2009).

[3] Tiedje, T., Yablonovitch, E., Cody, G. D. & Brooks, B. G. Limiting efficiency of silicon solar cells. *IEEE Trans. Electron Devices* **31**, 711-716 (1984).