Nano Energy (2015) 13, 9–17

Available online at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/nanoenergy

RAPID COMMUNICATION

Omnidirectional absorption enhancement of symmetry-broken crescent-deformed single-nanowire photovoltaic cells

Zhenhai Yang[a,b,1], Xiaofeng Li[a,b,*,1], Dang Yuan Lei[c,d], Aixue Shang[a,b], Shaolong Wu[a,b]

[a]College of Physics, Optoelectronics and Energy & Collaborative Innovation Center of Suzhou Nano Science and Technology, Soochow University, Suzhou 215006, China
[b]Key Lab of Advanced Optical Manufacturing Technologies of Jiangsu Province & Key Lab of Modern Optical Technologies of Education Ministry of China, Soochow University, Suzhou 215006, China
[c]Department of Applied Physics, The Hong Kong Polytechnic University, Hong Kong, China
[d]Shenzhen Research Institute, The Hong Kong Polytechnic University, Hong Kong, Shenzhen 518057, China

Received 20 December 2014; received in revised form 29 January 2015; accepted 5 February 2015
Available online 13 February 2015

KEYWORDS
Single-nanowire solar cells;
Crescent nanostructures;
Omnidirectional light-harvesting;
Symmetry breaking

Abstract
Single semiconductor nanowires enable a diverse range of applications in sensing, photodetection, and photovoltaics. Here we report that a delicate modification to the circular cross-section by eliminating a nanocrescent part can substantially strengthen the light-harvesting capability of a single nanowire. Despite the reduced photoactive material, the photocurrent density of the symmetry-broken crescent-deformed free-standing silicon single-nanowire solar cell can be counter-intuitively improved by over 45%. The excellent light-harvesting ability of the crescent-deformed nanowire can be maintained over a broad spectral band at a wide range of incident angle as corroborated by its dispersion relation. Under assistance of a metallic back reflector, the photocurrent enhancement ratio can be up to 66.2% without taking into account the material reduction. Our electrical evaluation shows that the new design leads to an enhancement ratio of light-conversion efficiency by 40.8%. This novel design by breaking structure symmetry represents a new pathway to realize highly efficient and compact photovoltaic devices with omnidirectional light absorption enhancement.

*Corresponding author.
E-mail address: xfli@suda.edu.cn (X. Li).
[1]The authors contribute equally to this study.

http://dx.doi.org/10.1016/j.nanoen.2015.02.007
2211-2855/

Introduction

As newly emerging photovoltaic devices, single-nanowire solar cells (SNSCs) have received considerable attention in recent years due to their compactness in size, outstanding light-harvesting capability, efficient carrier transportation/collection, and convenient integration into chips [1]. Besides the photovoltaic field, the unique structure/morphology characteristics of single nanowires (NWs) can find much diverse applications, e.g., light-emitting diodes [2,3], low-loss waveguides [4], thermoelectric devices [5,6], lithium batteries [7], and so on.

In photovoltaic applications, the light-harvesting capability is one of the most important factors in determining the light-conversion efficiency of a solar cell. This means that the nanowire absorption in SNSCs has to be high with broadband response in spectrum. Despite the antenna-effect-mediated strong absorption at short wavelengths, the overall performance of SNSCs is still far from expectation due to the narrow resonant bands and the relatively low absorption at long wavelengths. To improve the light-harvesting performance, properly engineering the structure parameters and cross-sectional morphology of the nanowires has been widely discussed in recent literatures [8-21]. It was shown that the light absorption in nanowire devices could be effectively engineered through control over the size, geometry and orientation of the nanostructure [8]. For instance, metal-core/semiconductor-shell nanocones were proposed and a broadband solar absorption enhancement was predicted by finite-difference time-domain (FDTD) simulation [9]. A dielectric core–shell design could work as an efficient optical antenna for solar incidence [10]. A semiconductor nanowire coupled into a super-wavelength metallic slit was proposed for a higher photodetection sensitivity [11]. Rectangular cross-section SNSCs were shown to have high external quantum efficiency (EQE) at long wavelengths, which benefited from the resonant modes excited within these highly symmetric structures [12]. For example, a core–shell rectangular SNSC based on gallium arsenide was designed to exhibit an enhanced EQE over a broad spectral range [13]. Moreover, it was claimed that the SNSCs with either circular, square, hexagonal, or triangular cross-sections actually exhibit similar optical response by taking into account the difference in the photoactive material volume [14]. In fact, there is indeed much room for further improvement of the light-harvesting performance of the SNSCs, by either decreasing the material usage or enhancing the absorption efficiency.

study, we coherently inspired by the broadband light-harvesting performance of the metallic nanocrescent structures designed by transformation optics [22,23] and the symmetry-breaking concept enabled generation of Fano resonances in plasmonic nanocavities [24-26], we proposed a new semiconductor nanowire design by simply eliminating a nanocrescent region from the circular cross-section without completely reshaping the geometry into square, hexagon or triangle. Such a slight modification to the nanowire, breaking the circular symmetry of its cross section, not only directly reduces the material consumption, but also substantially enhances the cell absorption in almost the whole visible and near infrared spectrum. Numerical simulations based on the finite-element method (FEM) indicate that the photocurrent density (J_{ph}) of a free-standing silicon (Si) SNSC device with optimal geometric parameters can be improved by 44.3% relative to the conventional circular design. Such a large absorption enhancement mainly arises from the multiple waveguide modes strengthened in the deformed symmetry-broken semiconductor nanocavity. In addition, the extraordinary light-harvesting capability can be well sustained under a wide range of oblique incidence over a broad spectral band. With incorporating a back metallic reflector, the photocurrent density of a 600 nm-diamter Si SNSC can be increased by 66.2%. Moreover, a thorough optoelectronic simulation verifies that a much higher η can be obtained from the crescent-deformed SNSCs. These new design paradigms open up many possibilities for achieving stronger light absorption with less photoactive material in a broad range of optoelectronic devices.

Model and methods

Devices of the model and the cross-sectional configuration of the crescent-deformed silicon SNSC is plotted in Fig. 1a, with four representative crescent designs exemplified in Fig. 1b-e. Compared to the conventional circular SNSC, in which the NW cross-section is purely characterized by the diameter *D*, the new system exhibits a controlled morphological modulation to the rear of the cell, i.e., a crescent part defined by *t* (the maximum distance between the inner and outer crescent boundaries) and θ (the angle between the tangents of internal and external circles in cross section) has been removed [22]. This delicate variation to the cross-sectional geometry not only directly shrinks the photoactive volume, but also effectively breaks the structure symmetry and consequently supports much intensive optical modes than the symmetric counterpart, leading to substantial enhancement of the photocurrent density as we will demonstrate later.

Numerical simulations based on FEM were performed to solve the Maxwell's equations for the SNSC system [27]. To calculate the electromagnetic modes in the single Si NW, the computational domain is surrounded by a perfectly matched layer and the solar incidence under AM1.5 spectrum is used [28]. The length of the lying nanowire is always

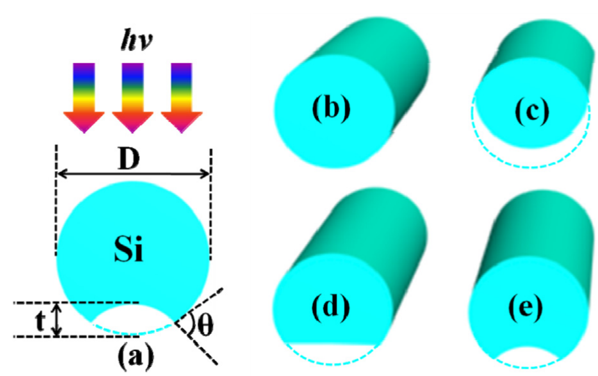

Fig. 1 (a) Schematic diagram of a crescent-deformed Si SNSC. Round NW (b) and various crescent-shaped NWs with (c) t/D=0.2 and θ=20°, (d) t/D=0.2 and θ=53°, and (e) t/D=0.2 and θ=80°.