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Short communication

Needle-shaped 3D dye-sensitized solar cells using anodized Ti wire and Pt nanoparticle/carbon fiber electrodes

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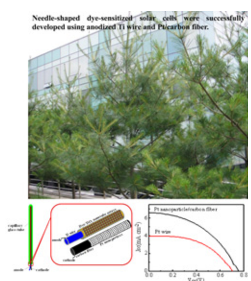
HIGHLIGHTS

- ► Needle-shaped dye-sensitized solar cells were developed using anodized Ti wire and Pt nanoparticle/carbon fiber.
- ► Pt nanoparticle/carbon fiber electrode exhibited high catalysis performance toward I_3^-.
- ► We explored its potential application in parallel connected situation.
- ► Carbon fiber was first employed as conductive substrate for counter electrode.

GRAPHICAL ABSTRACT



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ABSTRACT

Needle-shaped dye-sensitized solar cells are developed using anodized Ti wire and carbon fiber with Pt nanoparticle. The model cell is composed of N719 dye-sensitized TiO_2 nanotubes/Ti wire as working electrode, Pt nanoparticle/carbon fiber as a counter electrode and I^-/I_3^- electrolyte encased in a capillary glass tube with internal diameter of 1.0 mm and 40 mm in length. The as-prepared DSSC looks like a needle leaf of pine tree. The energy conversion efficiency is 2.21% which can be up to 3.07% after $TiCl_4$ post-treatment of photoanodes. In addition, higher current and output power can be obtained by parallel connection. Pt nanoparticle/carbon fiber is firstly used as counter electrode and the cyclic voltammetries investigation show that Pt nanoparticle/carbon fiber possess higher catalytic activity than Pt wire. Such type DSSC is TCO free and may be capable of achieving a long distance transport of photocurrent and harvesting all light from any direction in surroundings to generate electricity. It has been demonstrated that needle-shaped structure may be a good choice for a solar cell.

1. Introduction

Dye-sensitized solar cells (DSSCs) have been attracting extensive interest in scientific and industrial fields because of low manufacturing costs and high conversion efficiencies. [1] A conventional DSSC is usually based on a planar rigid fluorine-doped tin oxide (FTO) glass substrate with high costs and resistance, which is not suitable for transportation, installation, and remote application. In addition, the planar cell structure is a limitation for the full potential absorption of solar light. Moreover, the Pt counter electrode (CE) is an expensive noble metal, which can become a heavy burden for further development of DSSCs. All of these prevent the development of the large-scale industrial manufacturing of the DSSC. Until now, a variety of DSSCs have been designed to meet requirements, including the application of metal or carbonous substrates in DSSCs [2,3], three-dimensional (3D) DSSCs, [4–6] wire-shaped DSSCs, [7–10] and low Pt loading [11] or non-platinum DSSCs [12–14].

Many research efforts have been focused on the replacement of FTO glass with metal or carbonous substrate due to its good conductivity, low cost and high temperature endurance compared

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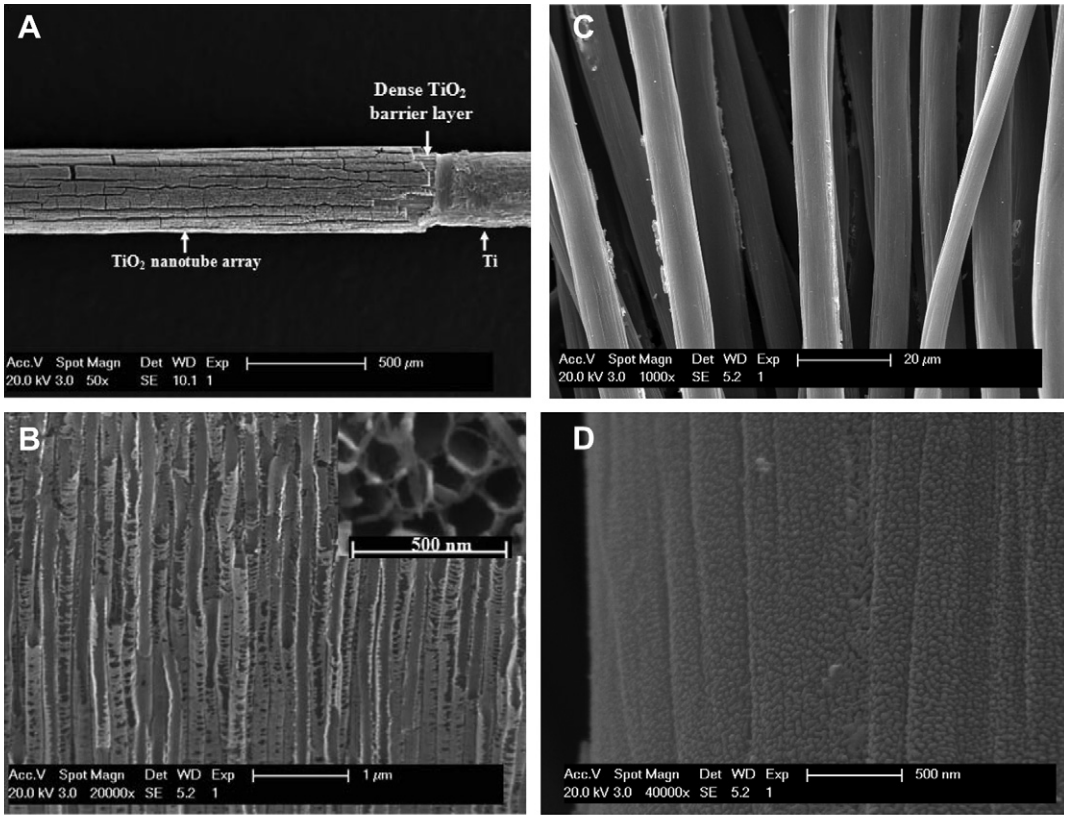

Fig. 1. FE-SEM characterization. (A) FE-SEM images of the photoanode with two parts, including an inner Ti core and anodically grown TiO_2 nanotube arrays. (B) Cross-section FE-SEM image of TiO_2 nanotube arrays grown around a Ti wire; the inset is the top morphology of TiO_2 nanotube arrays. (C) and (D) FE-SEM images of Pt nanoparticle/carbon fiber.

with the FTO substrate. Zou et al. [2] fabricated the first generation of all-metal DSSC by using stainless steel mesh as the substrate and coated it with dense and porous TiO_2 layers. The conversion efficiency is about 1.49%. Guo et al. [3] reported rectangular bunched rutile TiO_2 nanorod arrays grown on carbon fiber was used successfully as photoanode in DSSC and energy conversion efficiency of 1.28% was achieved. Carbon fibers are flexible, conductive and stable in liquid electrolyte. They also have large surface area and good heat resistance and fatigue. Thus, they could be promising candidates for conductive substrates in DSSCs.

The counter electrode affects the performance of the DSSCs by modifying the electrical conductivity and the catalytic activity for the regeneration of the I_3^-/I^- species. Platinum is the most superior counter electrode material with excellent catalytic activity and high electrical conductivity. However, the high price of Pt undoubtedly limits its application for large-scale production of DSSCs. Therefore, many research efforts have been focused on exploiting inexpensive substitutes for Pt, such as carbon materials [15,16], conductive organic polymers [17,18], and inorganic materials [19]. In addition, reducing the loading amount of Pt is another alternative method to reduce the costs [11].

Titania has been proved to be one of the most promising candidates for photoanodes until now [20–24]. The use of TiO_2 nanotubes in conventional planar DSSCs can effectively improve the charge collection efficiency [25–28]. Very recently, using TiO_2 nanotube arrays on Ti wires have been reported [4,29,30]. Liu et al. [30] demonstrated a prototype dye-sensitized photovoltaic wire with a conversion efficiency of 2.78% using anodized Ti wire as working electrode and platinum wire as counter electrode. The advantages of Ti wire have been realized but there is great challenge to enhance its conversion efficiency and to decrease its cost by exploiting inexpensive substitutes for Pt wire.

3D DSSCs exhibit superiority of absorbing sun light from all directions. Wang et al. [4] fabricated a 3D DNA-like structure dye-sensitized solar cell with all-Ti substrates, which showed superiority of light utilization due to its symmetrical double-helix structure. Weintraub et al. [5] demonstrated an optical fiber/nanowire hybrid structures for efficient 3D three-dimensional dye-sensitized solar cells. The optical fiber is used as a channel of the light incident and the internal reflection of the light within it creates multiple opportunities for energy conversion.

In the nature, many kinds of plant leaves have been evolved to capture the solar energy more effectively. For example, the needle leaves of pine tree grown around the stem in orderly screw pattern can avoid shading each other and is not sensitive to the sun azimuth. Inspired by the needle leaves of pine tree, we fabricated a needle-shaped 3D structure of DSSCs in this work. The conversion efficiency is 3.07% using highly ordered TiO_2 nanotube arrays radically grown around a Ti wire post treated by $TiCl_4$ and Pt nanoparticle/carbon fiber as the counter electrode. The Ti metal wire and carbon fiber played a key role in reducing the internal resistance of DSSCs. As far as we are aware, this is the first time that carbon fiber is used as the counter electrode substrate. In addition, the cells in parallel were also achieved for the first time. It has been demonstrated that needle-shaped structure may be a good design for a solar cell.

2. Experimental section

2.1. Fabrication of the photoanode

The titanium wires (0.4 mm) were chemically etched by dipping in an HF (40%)–HNO_3 (65%)–H_2O (1:4:5 in volume) solution for 20 s. The etched wires were repeatedly rinsed in deionized water