Nano Energy (2014) **9**, 291–300

Available online at www.sciencedirect.com

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

RAPID COMMUNICATION

Silicon-based hybrid cell for harvesting solar energy and raindrop electrostatic energy

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Received 25 June 2014; received in revised form 14 July 2014; accepted 31 July 2014
Available online 19 August 2014

KEYWORDS
Hybrid cell;
Triboelectric nanogenerator;
Solar energy;
Raindrop electrostatic energy;
Energy harvesting

Abstract
Silicon-based solar cell is by far the most established solar cell technology. The surface of a Si solar cell is usually covered by a layer of transparent material to protect the device from environmental damages/corrosions. Here, we replaced this protection layer by a transparent triboelectric nanogeneartor (TENG), for simultaneously or individually harvesting solar and raindrop energy when either or both of them are available in our living environment. The TENG is made of a specially processed polytetrafluoroethylene (PTFE) film, an indium tin oxide (ITO) and a polyethylene terephthalate (PET) layer. Under solar light irradiation (12 W/m^2) in a rainy day, the fabricated high-efficiency solar cell provides an open-circuit (V_{oc}) of 0.43 V and short-circuit current density (J_{sc}) of 4.2 A/m^2. And the TENG designed for collection of raindrop energy gives an AC V_{oc} of 30 V and J_{sc} of 4.2 mA/m^2 when impacted by water drops at a dripping rate of 0.116 ml/s. In rainy days, the performance of solar cell decreased greatly, while TENG can be a good compensation as for green energy harvesting. From these results, we can see that the hybrid cell formed by a solar cell and a water-drop TENG have great potential for simultaneously/individually harvesting both solar energy and raindrop electrostatic energy under different weather conditions, especially in raining season.
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http://dx.doi.org/10.1016/j.nanoen.2014.07.024
2211-2855/Published by Elsevier Ltd.

Introduction

Energy crisis and environmental pollution have been the main challenges for a sustainable development of the world [1,2]. Harvesting energy from the natural environment such as solar [3,4], wind [5], biomass energy [6], mechanical vibration [7,8] and wasted heat [9,10], has attracted great interest in academic research in the past decades. Silicon based solar cells gradually become the most widely used commercial technology for large scale harvesting of solar energy because of its low cost and superior performance [11]. However, low conversion efficiency is still the main limiting factor for current technologies. A large portion of energy loss during solar-cell operation is attributed to the loss of incoming light by reflection [12]. To reduce the reflection loss, surface texturing [13-15] such as fabrication of various surface pyramid structures is often used to enhance light trapping by multiplying the internal reflections [13]. On the other hand, the solar cell panels have to be placed in ambient harsh environment with contaminations, corrosions, and varying weather conditions. In sunny days, solar cells can provide much electricity through photovoltaic effects. But in rainy days/season and night, the output of solar cells maybe largely suppressed or even vanished.

Currently, triboelectric nanogenerator (TENG) based on contact electrification and electrostatic induction effect has been developed to convert various forms of mechanical energy in the environment into electricity [16-21]. When two material surfaces with opposite triboelectric polarities are periodically contacted and separated, a periodic potential difference between the two electrodes on their backs varies, which drives electrons to flow through the external circuit and generate an AC electrical output [22]. Recently, triboelectrification on the water/solid [23] and water/air [24] interfaces are used to develop a new type of TENG, which demonstrates promising applications for harvesting energy from ocean wave, tide, and rain water in the environment [25,26].

In practical applications, the surface of a solar cell is usually covered by a layer of transparent material to protect the device from environmental damages/corrosions. Since a water-drop TENG can be fabricated using highly transparent polymer materials, we could just replace the regular protection layer on solar panel using a specially designed and processed transparent polymer layer, to achieve the dual function of being a protection layer and a TENG. In this paper, we demonstrated a hybrid energy cell that consists of a specially designed micropyramidal Si solar cell and a water-drop TENG for simultaneously/individually harvesting both solar and raindrop electrostatic energy.

Experimental section

Fabrication of Si solar cell with micropyramids

The Si substrate used was a single-crystal, p-type float-zone substrate with a thickness of 300 μm. The textured Si surface with micropyramids was created by KOH etching. The wafer was then cleaned to remove surface organic and metallic contaminants, followed by $POCl_3$ diffusion to form the n^+-emitter. A diffusion temperature of 1133 K was used to obtain a 65 Ω/sq emitter. The wafer was then coated with 80 nm SiN via a plasma-enhanced chemical vapor deposition reactor. The SiN film serves as a passivation and antireflection coating layer for the device. After that, the screen-printed n^+-p-p^+ junction solar cell was fabricated. An Al paste was screen-printed on the backside of the Si substrate and dried at 473 K. Ag grids were then screen-printed on top of the Si substrate, followed by cofiring of both the Ag and Al contacts. An ITO top electrode with 300 nm thickness was coated by PVD 75 RF sputter.

Fabrication of the superhydrophobic PTFE thin film

First, microstructures were fabricated by blasting an Al foil with sand particles using compressed air. The sand-blasted Al foil was further anodized in a 0.3 M oxalic acid solution to obtain an anodic Al oxide (AAO) template with nanometer-sized holes. An SEM image of the AAO template is shown in Figure S2, where the average diameter of the holes in AAO template is about 46 nm. Then after using a self-assembled monolayer of a heptadecafluoro-1,1,2,2-tetrahydrodecyl trichlorosilane (HDFS) to lower the surface energy of the AAO template, PTFE solvent was poured into the AAO template and a conventional vacuum process was applied to remove the air remaining in the nanoholes. After curing at the ambient temperature for one day, the solvent was evaporated and a PTFE thin film was left with hierarchical nanostructures. Finally, the PTFE thin film was peeled off from the AAO template by using a transparent double-sided tape.

Fabrication of hybrid cell

A commercial ITO film with thickness of 100 nm and PET thin layer was used as the electrode for water-drop TENG, and then a PTFE thin film was attached onto the ITO surface, thus a water-drop TENG was fabricated. Then the fabricated water-drop TENG was put onto the surface of Si-based solar cell. Finally, some PDMS mixture with elastomer and cross-linker (Sylgard 184, Dow corning) mixed in a 10:1 mass ratio was used to seal all the electrodes of the device to prevent it from water.

Measurement of hybrid cell

The solar cell efficiency was characterized under the light illumination intensity of 1000 W/m^2. The *I–V* curves of Si-based solar cell before and after integrating the water-drop TENG was measured by using a Keithley 4200 semiconductor characterization system. The spectra transmittance of the TENG was measured by a UV–vis spectrophotometer (V-630). In the electric output measurement of the TENG, the water drops were sprayed by a shower which was connected to a household faucet and the water dripping rate was controlled by the knob of the shower. The current meter (SR570 low noise current amplifier, Stanford Research System) and voltage meter (6514 system electrometer, Keithley) were used to measure the electric output of the water-drop TENG.