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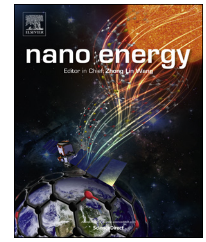

RAPID COMMUNICATION

High-performance hybrid cell based on an organic photovoltaic device and a direct current piezoelectric nanogenerator

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Abstract
The search for harvesting both the mechanical and solar energies from a single hybrid system is of significant value and represents a new trend in energy harvesting technologies. This single hybrid system can utilize both the energy sources easily available from nature and most importantly it is clean and sustainable. It is a novel technique involving completely different physical principles utilized for scavenging different types of energies. This report presents studies of a hybrid power generator made a direct-current piezoelectric nanogenerator based on ZnO nanosheets and a bulk heterojunction organic solar cell based on an inverted structure. The device shows much larger electric power output compared to its two individual power output components, which facilitates more effective multi-type energies harvesting and clarifies a mechanism for realizing multi-functional energy devices.

Introduction

New energy harvesting devices have developed considerably in recent decades, due to the continuous growth in the demand for renewable energy sources, the increasing need

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to reduce global warming and the continued depletion of fossil fuels in modern society [1–5]. Harvesting mechanical, thermal, magnetic, chemical, and light energies from living environments is one of the most urgent challenges for the sustainable development of human civilization and has critically importance for powering small scale portable electronics, self-powered body-implanted devices, and self-powered sensors [6–9]. Recently, intensive research has focused on developing various types of photovoltaic devices for harvesting solar light energy; of these, organic materials-based photovoltaics as energy harvesting devices have proven to be important since they are flexible, eco-friendly, and easy to process. Further very effective power conversion of organic solar cells (OSCs) under indoor illumination compared to other solar cells should be noted [10–12].

In addition, many types of mechanical energy scavenging devices such as a piezoelectric nanogenerator (PNG) have attracted considerable attention for self-powering small scale devices including sensors and wearable electronics [13–19]. Among the various piezoelectric materials utilized for fabricating PNGs, the ZnO nanostructures have been regarded as the most popular building blocks owing to their semiconducting and piezoelectric coupling properties [20,21]. Furthermore, harvesting both mechanical and solar energies from a single hybrid system is currently highly desirable and represents a new trend of all-in-one multiple energy harvesting technologies [22]. Moreover, because of the completely different physical principles utilized for scavenging different types of energies, each type of corresponding conversion device involves an independent unit. Therefore, innovative approaches can be developed for the conjunctional harvesting of multiple types of energies using an integrated structure so that the energy resources can be effectively and complementarily utilized whenever and wherever one or all of the energy resources are available.

Recently, although harvesting both solar and mechanical energies at the same time from a single hybrid cell based on both a one-dimensional (1D) ZnO nanorod-based PNG and a solar cell has been demonstrated in the previous researches [23–26], the effect on the total performance of the hybrid cell due to the different nature of the piezoelectric output signals from PNG has not been clearly investigated and discussed. In the reported hybrid systems, due to the alternative current (AC) piezoelectric output from PNGs and the direct current (DC) output electric signal from the solar cell, the total output from the hybrid cell is degraded significantly during rectification. Nevertheless, the output current generated from PNG in the hybrid system is quite low compared to that in the solar cell, thus restricting the wide application of the hybrid cell for powering small scale electronic devices.

In the present article, we report the fabrication of a hybrid system consisting of a highly efficient DC type PNG (DC-PNG) based on 2D ZnO nanosheets and an OSC based on poly(3-hexylthiophene) (P3HT) and [6,6]-phenyl-C_{61}-butyric acid methyl ester ($PC_{60}BM$) for harvesting multiple type energies, i.e. solar energy and mechanical energy simultaneously/individually. We also demonstrate the high DC output current from the PNG cell under vertical compressive force/pressure and high output performance from an OSC separately under light illumination. Our approach relies on the connection of the anode of the OSC with the cathode of PNG to harvest solar and mechanical energy under external mechanical force and light illumination. The power-generating performance of the serially integrated hybrid cell (s-HC) is synergistically enhanced by the contribution of a PNG, compared with the output power

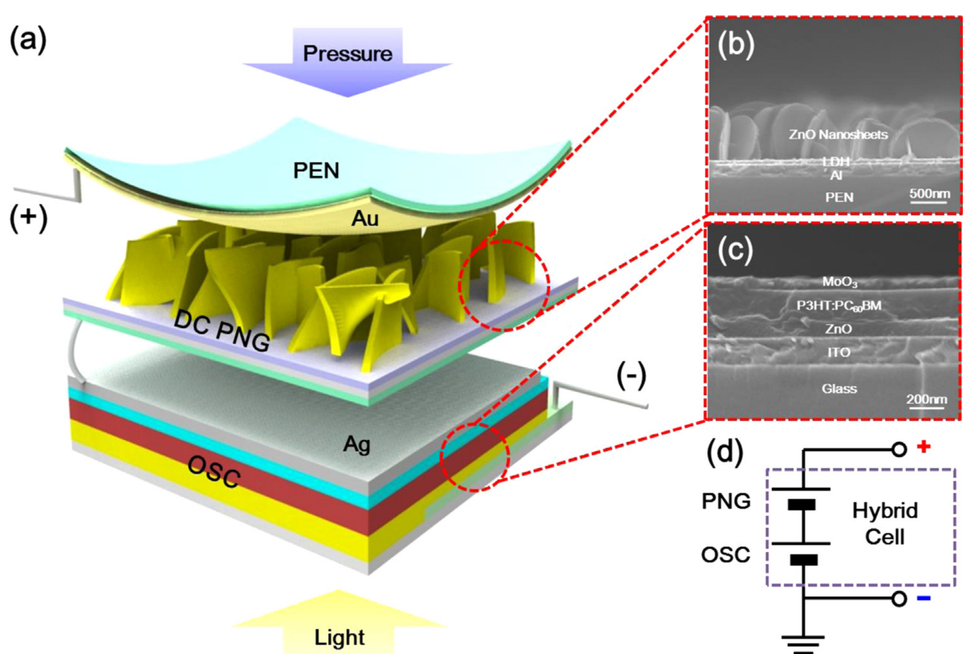

Figure 1 Design of a s-HC for simultaneous harvesting of mechanical and solar energies under external mechanical force and light illumination. (a) 3D schematic representation of a s-HC. (b) Cross-sectional FE-SEM image of ZnO nanosheets grown on an Al film. (c) Cross-sectional FE-SEM image of the inverted OSC structure. (d) A schematic showing equivalent circuit of the s-HC based on OSC and DC-PNG.