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RAPID COMMUNICATION

Hybrid energy cells for simultaneously harvesting multi-types of energies

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Abstract
Harvesting multi-mode energies from our living environment is an effective approach for solving the power source issue of the sensors and some personal electronics. Usually, the mechanical, thermal, and solar energies can be extensively found in our living environment. However, these energies are not always available at the same time, which is depending on the weather, working conditions, and some other cases. The concept of a hybrid energy cell is to develop a technology to individually or simultaneously scavenge multi-mode energies from environment, so that the sensors or other devices can sustainably work without the external power sources. In this article, we review the investigations about the hybrid energy cells that include the energy harvesting units such as the piezoelectric nanogenerator, triboelectric nanogenerator, pyroelectric nanogenerator, thermoelectric generator and solar cells. The fabricated hybrid energy cells have been utilized to light up some electronics and for some self-powered electro-chemical applications. The obtained energies can be also stored in Li-ion battery, where the hybrid structure between the nanogenerator and the Li-ion battery exhibits the better charging performance than that of the conventional charging method. These investigations are of critical importance for sensing, medical science, environmental monitoring, defense technology, and even personal electronics.

Introduction

Our living environment has an abundance of energies in the forms of mechanical, optical, thermal and chemical energies. Scavenging these types of energies is of critical importance for long-term energy needs and sustainable

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development [1]. However, these energies are not always available at the same time, which depends on the weather, working conditions, and some other cases. The purpose for developing the hybrid energy cells is to simultaneously/individually scavenge these energies by using an integrated device, so that the devices/sensors can be continuously powered by using whatever energy that is available at their environment. The hybrid energy cells have the potential for fully utilizing the multimode energies in the environment under which the sensors/devices will be continuously and stably operating.

In last five years, we have developed many kinds of hybrid energy cells for simultaneously harvesting multi-types of energies, which not only can enhance the conversion efficiency of energy devices, but also has the potential applications in the self-powered electronics and some electrochemical reactions. The different energy harvesting units can work simultaneously or individually, and can be integrated in serial and parallel for enhancing the output voltage and current, respectively. The object of this article is to give a summary about the development of the hybrid energy cells. These investigations have demonstrated many innovative approaches for developing integrated technologies for effectively harvesting available energies in our environment.

Hybridization based on piezoelectric nanogenerators

Hybrid piezoelectric nanogenerator and solar cell for harvesting mechanical and solar energies

In 2009, a hybrid energy cell was intended for simultaneously scavenging the mechanical and solar energies [2]. As shown in Figure 1a, the hybrid energy cell consists of a dye-sensitized solar cell on the top surface for scavenging the solar energy and a piezoelectric nanogenerator on the bottom surface for harvesting ultrasonic wave energy from the surroundings. Figures 1b and 1c illustrate the SEM images of the ZnO nanowires, which were used as functional materials in both the solar cell and the piezoelectric nanogenerator. In the solar cell, ZnO nanowires coated with dye molecules were separated from the counter electrode by a gap in the electrolyte. In the piezoelectric nanogenerator, the ZnO nanowires were periodically bent/deflected by the ultrasonic wave to approach and contact the top zigzag electrode to realize the current/voltage output. Figure 1d displays the working principle of the hybrid energy cell by using the electron energy band diagram. The working of piezoelectric nanogenerator is due to the strained

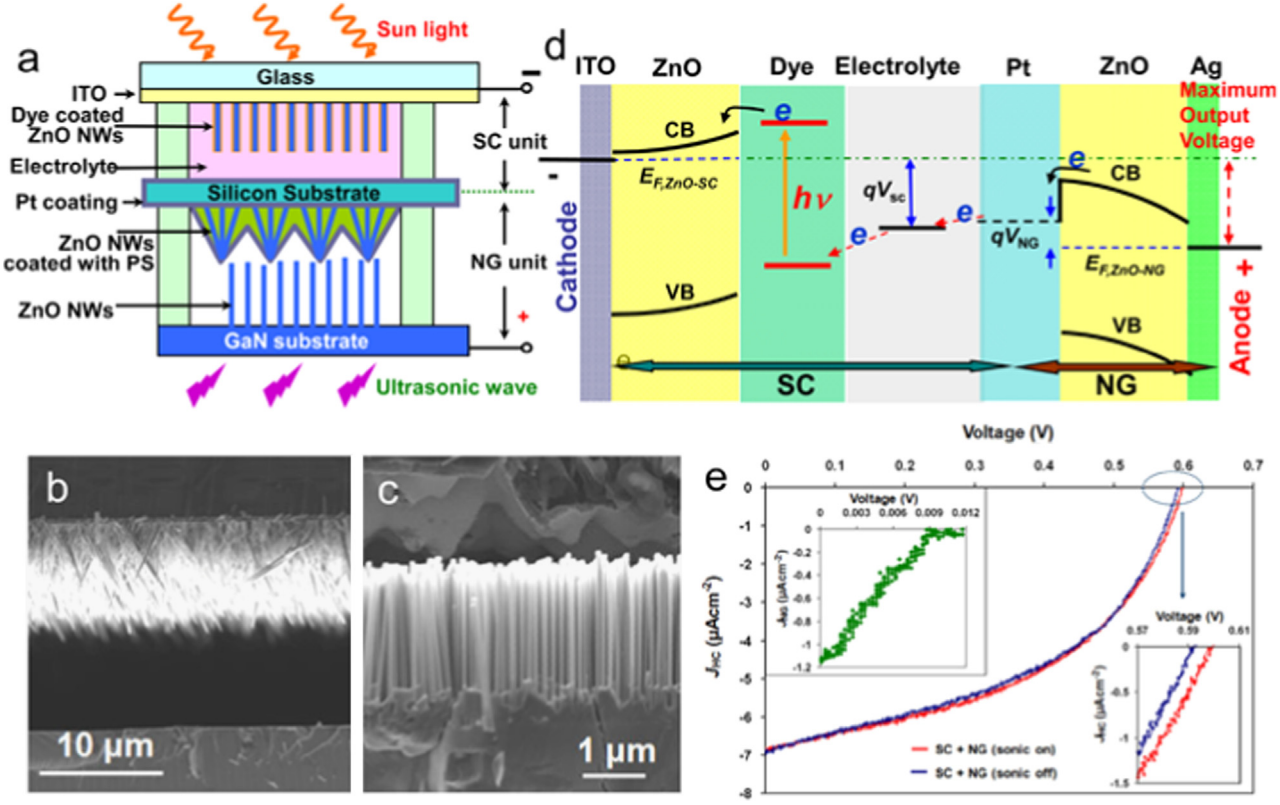

Figure 1 (**a**) Schematic diagram of serially integrated hybrid energy cell. (**b**) SEM image of the solar cell unit. (**c**) SEM image of the nanogenerator unit. (**d**) Electron energy band diagram of the hybrid energy cell. (**e**) A comparison of *J-V* characteristics of a hybrid energy cell when illuminated by simulated sun light with (red curve) and without (blue curve) turning on the ultrasonic wave excitation. The inset is an expanded output of the open-circuit voltage points around the axial cross point. Reproduced form Ref. [2] Copyright 2009 American Chemical Society.