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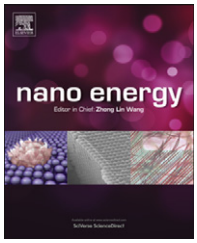

REVIEW

Hybrid cells for simultaneously harvesting multi-type energies for self-powered micro/nanosystems

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Abstract
Our living environment has an abundance of energies in the forms of light, thermal, mechanical (such as vibration, sonic wave, wind, and hydraulic), magnetic, chemical, and biological. Harvesting these types of energies is of critical importance for long-term energy needs and sustainable development of the world. Over the years, rationally designed materials and technologies have been developed for converting solar and mechanical energies into electricity. Photovoltaic relies on approaches such as inorganic *pn* junctions, organic thin films, and organic-inorganic heterojunctions. Mechanical energy generators have been designed based on principles of electromagnetic induction and piezoelectric effect. Innovative approaches have to be developed for conjunctional harvesting of multiple types of energies using an integrated structure/material so that the energy resources can be effectively and complimentarily utilized whenever and wherever one or all of them are available. We give a review on the hybrid cells that are designed for simultaneously harvesting solar and mechanical, and chemical and mechanical energies using nanotechnology. The two energy harvesting approaches can work simultaneously or individually, and they can be integrated in parallel and series for raising the output current and voltage, respectively. Innovative approaches have been demonstrated for developing integrated technologies for effectively scavenging available energies in our environment around the clock.

Introduction

Most of today's energy comes from the fossil fuel, which unfortunately produces a considerable amount of CO_2 emission that causes numerous problems. To ensure sustainable development of our society, we must not only develop renewable energy courses but also find other innovative solutions to the problem. Currently, the renewable energy comprises only 5.14% of the energy production [1] worldwide (Fig. 1), so considerable effort has gone to renewable energy harvesting [2], such as solar [3–10], hydroelectric [11,12], wind [13], and hydrothermal energy [14,15].

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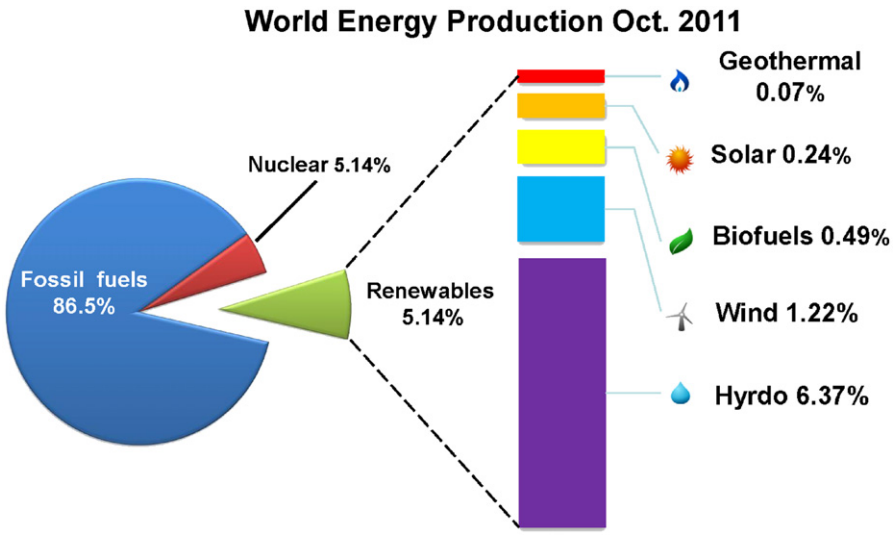

Figure 1 Pie chart of the world energy production in October 2011 with the renewable distribution.

Although it is rather challenging to solve the large-scale world energy need, energy harvesting is a technology by which ambient energy is extracted from the environment and converted into electricity to power electronic devices. Researchers have developed several approaches for harvesting solar, thermal, mechanical, and chemical energies, but all of the approaches are targeted at one type of energy for one type of particular applications, while the rest of the other types of energies are wasted. A solar cell, for example, is only designed to harvest the energy from the sun, but the energy from the heat generated by the sun light is ignored. To fully utilize the energy in the environment, a hybrid cell [16] (HC) has been first proposed by Wang's group for simultaneously harvesting multi-type energies using a single generator (e.g., a hybrid cell that harvests both solar and mechanical energy [17] instead of one single source). As the number of personal electronics and mobile electronics is rapidly increasing, we desperately need technologies that can achieve maintenance-free and sustainable operation of micro-electromechanical systems (MEMS), wireless electronics, and biomedical sensors. The hybrid cells are being developed to fully utilize the energies that are available to us.

Semiconductor one-dimensional nanostructures [18,19], a subset of these materials, have received significant attention for their unique properties and complex structures especially in energy harvesting technology. Many nanostructure-based materials are promising candidates for multi-type energy harvesting devices. The birth of HC devices could be important for developing innovative technologies towards maintenance-free, self-powered systems [20] without batteries or at least extend the lifetime of batteries. This is particularly attractive for wireless sensor networks, environmental monitoring, biomedical devices, and personal electronics.

This review summarizes the basic principles and approaches of HCs that have been developed using nanowires. Some basic applications for powering UV sensor, pressure sensor, and LED will be illustrated. We anticipate that the article will stimulate relevant research in the field so that the hybrid cell can be a distinct and disciplinary in the field of energy science and technology.

The importance of multi-type energy harvesting

In the working environment of a nanosystem or microsystem, the energy available for driving the system could vary from time to time and from location to location. This is especially true for mechanical vibration energy and solar energy. Solar is probably the most abundant energy that we are interested in, but solar is not always available, strongly depending on day, night, and weather. Mechanical energy is location-dependent, which may not be suitable for mobile electronics. To effectively utilize the energies that are available at a given time and location, a generator is required for converting all types of energies, such as solar, thermal, mechanical, and chemical, into electricity. A wireless environmental sensor, for example, is an emerging technology that can reliably measure various conditions in civil, aerospace, and biomedical applications. One of the major drawbacks of wireless sensors is that they require considerable power. In some remote locations, supplying power through cables, or using disposable energy sources, is often impractical, if not impossible.

Thus developing HCs according to a systematic approach would be highly advantageous. After the first nanowire-based HC device was demonstrated for concurrently harvesting solar and mechanical energy in 2009 [16], it inspired a number of researchers to work on developing such technology. Since then, many more HCs for multi-type energy harvesting including biomechanical and biochemical energies and also solar and acoustic energies have been demonstrated. The following sections will review several innovative ways in which multi-type energies can be harvested based on nanostructure-based HCs.

Hybrid cell: from mono- to multi-type energy harvesting

Photovoltaic cells or solar cells are a popular renewable energy technology. However, solar cells do not work well without sufficient sun light, necessitating a supplementary battery for the harvesting system and limiting their adaptability to certain applications. Considering the fact