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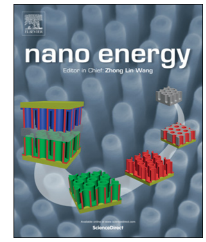

Recent progress in piezoelectric nanogenerators as a sustainable power source in self-powered systems and active sensors

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Abstract
Mechanical energy sources are abundant in our living environment, such as body motion, vehicle transportation, engine vibrations and breezy wind, which have been underestimated in many cases. They could be converted into electrical energy and utilized for many purposes, including driving small electronic devices or even constructing an integrated system operated without bulky batteries and power cables. Many progresses have been made recently in the mechanical energy harvesting technology based on piezoelectric nanogenerators (PENGs). By introducing a new sandwich structure design, high performance PENGs can be achieved through very simple fabrication process with good mechanical stability by utilizing ZnO nanowires (NWs). By further optimizing the nanomaterials' properties and device structure, the PENG's open circuit (OC) voltage can be elevated to over 37 V. Two important applications of this technology are that the nanogenerator can be used as a sustainable power source for self-powered system and can worked as active sensors. Several demonstrations are reviewed here. Finally, perspectives of this mechanical energy harvesting technology are discussed. Co-operation with power management circuit, capability of integrating with a system, and low cost large-scale manufacturing processing are suggested to be the key points toward commercialization of PENGs.

Introduction

The development of technology brings us a smarter world, and also makes us to be more dependent on electronic equipment. As the size and power consumption shrinks day by day, harvesting energy from the working environment to power

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electronic devices is a promising way. It is especially feasible for the applications in sensor networks and personal consumer electronics, which can extend their capability by getting rid of batteries and power cables. There are many kinds of energy sources in the environment, such as mechanical energy, thermal energy, chemical energy, solar energy, nuclear energy, *etc.*, which are all represented in various forms, as shown in Figure 1. Distinguished from others, mechanical energy is the one that is available almost everywhere and at all the time. It can come from gentle airflow, ambient noise, vibration, human body activity, *etc.*, which is suitable for the purpose we mentioned above. But, the amplitude and frequency of the mechanical energy source in the environment are usually random. That means we need to find a proper energy harvesting approach that has a tolerance for variable environments which is differ from the traditional cantilever based resonators [1] and [2] and electromagnetic induction based electrical generator [3] and [4]. The technology of piezoelectric nanogenerator (PENG) [5] was first proposed in 2006. It converts random mechanical energy into electric energy by using piezoelectric ZnO nanowires (NWs), which can be triggered by tiny physical motions and work in a large frequency range. Also ZnO is non-toxic and biocompatible, which is very critical for the sustainable energy technology used in our living environment. At the very beginning, we are more focused on the science behind the phenomenon [6-10], and it took a long journey to bring this technology from a scientific concept to a practical technology. For example, it took 4 years to raise the open circuit (OC) voltage from the original 9 mV to over 1 V [11-14]. Even so, the sophisticated device fabrication process sets up a barrier for the further development of this technology. Recently, new device design based on a sandwich structure was proposed, by which high performance PENG can be achieved with greatly simplified fabrication process and high mechanical stability by utilizing ZnO NWs. we will review two representative sandwich structure device designs and compare the working mechanism with previous devices based on Schottky contact structure. One very important application of the PENGs is that they can be used to construct self-powered systems, which harvest energy from the working environment and convert it into electricity to realize maintenance-free and sustainable operation of the system. PENGs can also work as active sensors. It is triggered by the mechanical deformation from the environment, and an electrical signal will be generated. That means no extra power source is needed here at least for the sensor tip [15]. In this review, several demonstrations of self-powered systems and active sensors by integrating PENGs will be illustrated. At the end, perspectives of this mechanical energy harvesting technology are discussed.

High output PENGs with new design

Sandwich structure vs. the Schottky contact structure in PENGs

At the early stage, the Schottky contact formed at the metal-ZnO interface is considered to play an important role on the output performance of PENGs [5], [9], [10] and [13]. In such a device design, two metal-semiconductor contacts form at the

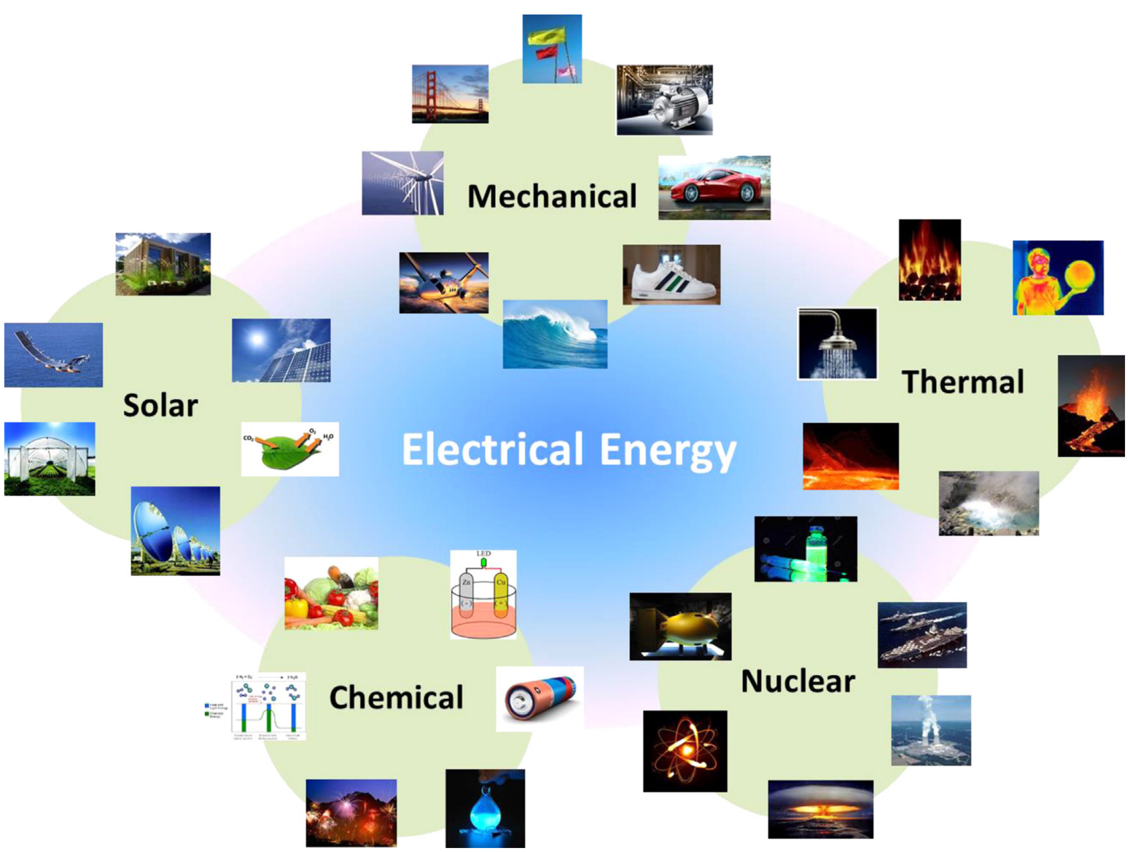

Fig. 1 Various available energy sources in the environment and their representative forms.

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