Top emerging technologies for self-powered nanosystems: nanogenerators and nanopiezotronics

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Abstract- **Developing wireless nanodevices and nanosystems are of critical importance for sensing, medical science, defense technology and even personal electronics. Power sources are indispensable for independent, sustainable, maintain-free and continuous operations of implantable biosensors, ultrasensitive chemical and biomolecular sensors, nanorobotics, micro-electromechanical systems, remote and mobile environmental sensors, homeland security and even portable/wearable personal electronics. It is highly desired for wireless devices and even required for implanted biomedical devices to be self-powered without using battery. This is a key step towards *self-powered nanosystems* [1]. The near future research is the integration of multi-functional nanodevices into a nanosystem so that it can function as a living species with capabilities of sensing, controlling, communicating and actuating/responding. A nanosystem is composed of not only nanodevices but also nano-power-source (or nano-battery). We now consider the following occasions. In cases where individual sensors are difficult to get to (e.g., in hostile territory), or if the sensor network consists of a large number of nodes distributed over a large geographic area, then it may not be possible to replace batteries when required. A self sufficient power source deriving its power from the environment and thus not requiring any maintenance would be very desirable. In order for any system to be self sufficient, it must harness its energy from its surrounding environment and store this harnessed energy for later use. The goal for nanotechnology is to build self-powered nanosystems that exhibit ultrasmall size, supersensitivity, extraordinary multi-functionality and extremely low power consumption.**

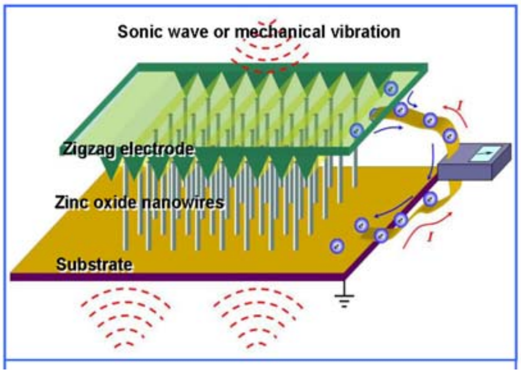

Figure 1. Schematic diagram showing the direct current nanogenerator built using aligned ZnO nanowire arrays with a zigzag top electrode. The nanogenerator is driven by an external ultrasonic wave or mechanical vibration and the output current is continuous.

For a piezoelectric material, a piezoelectric potential is created once it is subjected to a strain. The piezopotential is created due to the polarization of the ions in the crystal. This potential can have two functions. One, it can drive a transient flow of the electrons in the external circuit, which is a process of generating electric energy. This is the fundamental principle of the nanogenerator. The other is that it can gate the flow of charge carriers flowing through the material if it is a semiconductor, resulting in piezopotential gated field effect transistors, diodes and sensors. This is the principle of piezotronics

1. NANOGENERATORS FOR HARVESTING MECHANICAL/ULTRASONIC ENERGY

We have demonstrated an innovative approach for converting nano-scale mechanical energy into electric energy by piezoelectric zinc oxide nanowire (NW) arrays [2]. The operation mechanism of the electric generator relies on the unique coupling of piezoelectric and semiconducting dual properties of ZnO as well as the elegant rectifying function of the Schottky barrier formed between the metal tip and the NW. Based on this mechanism, we have recently developed DC nanogenerator driven by ultrasonic wave in bio-fluid [3]. We have also used textile fibers for energy harvesting [4].

2. LATERALLY-PACKAGED SINGLE-WIRE GENERATOR

Single-wire generator (SWG) is based on cyclic stretching-releasing of a piezoelectric fine-wire (PFW), which is firmly contacted at both ends with metal electrodes, laterally bonded and packaged on a flexible substrate [5]. A repeated stretching-releasing of a single PFW with strain of 0.05-0.1% creates an oscillating output voltage up to ~50 mV with the energy conversion efficiency of the wire itself being up to 6.8%. The schematic diagram and experimental data for the first SWG was provided in 2. More recent work has shown the output voltage can be significant improved, with integrated SWGs reaching 0.1-0.15 V. The nanogenerators have been demonstrated as potential technology for harvesting energy from body movement [6].

3. HYBRID CELL FOR CONCURRENTLY SCAVENGING SOLAR AND MECHANICAL ENERGIES

Conversion cells for harvesting solar energy and mechanical energy are usually separate and independent entities that are designed and built following different physical principles. Developing a technology that harvests multiple-type energies in forms such as sunlight and mechanical around the clock is desperately desired for fully utilizing the energies available in our living environment. We have developed a hybrid cell that is designed for simultaneously harvesting solar and mechanical energies [7].

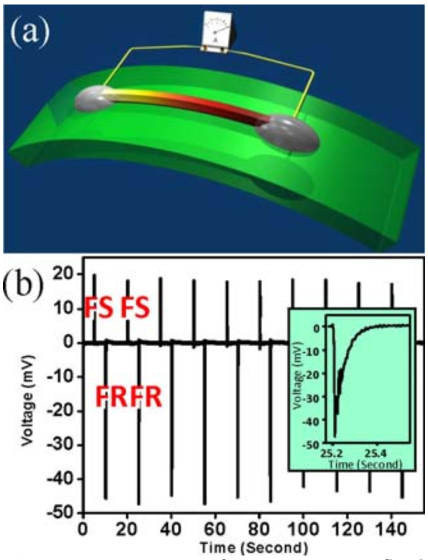

Figure 2. (a) Design of an SWG on a flexible substrate (b) Generated alternating voltage of an SWG when repeatedly fast-stretched (FS) and fast-released (FR).

4. NANO-PIEZOTRONICS

The basis of piezotronics is to use the coupled piezoelectric and semiconducting properties of nanostructures for designing and fabricating electronic devices and components, such as FETs and diodes [1, 8]. The main materials used for the current studies are ZnO 1D nanostructures, such as NWs and nanobelts. Due to the unique coupled semiconducting and piezoelectric property, a ZnO NW can generate a potential drop across its cross-section once it is bent by an external force. The stretched surface is positive and the compressed surface is negative (Fig. 3). If the potential is large enough, it can play the role as the gate voltage for FET. By connecting a ZnO NW across two electrodes that can apply a bending force to the NW, the electric field created by piezoelectricity across the bent NW serves as the gate for controlling the current flowing through the NW. Based on the same principle, piezo-sensor and piezo-switch have been developed [9, 10,11].

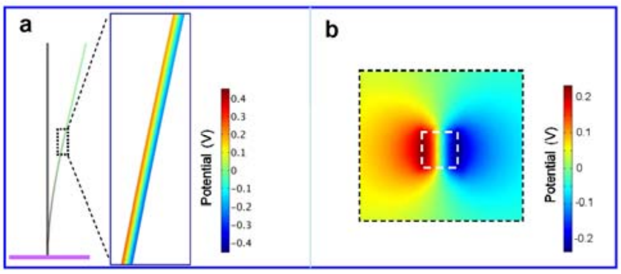

Figure 3. (a) Calculated piezoelectric potential distribution in a rectangular ZnO wire once it is bent for a nanowire without doping. (b) A cross-sectional of the potential distribution.

The PE-FET and PE-diodes are two key devices ruled by the theory of Piezotronics. They also set the foundation of our proposed nanosensors and nano-triggers. Driven by mechanical perturbation, these devices exhibit unique advantages over traditional FET devices in power consumption, sensitivity, life time and work environments. A brand new area of nanoelectronics is expected to be created with the establishing of Piezotronics theory and the development of novel piezotronic nanodevices.

The nanogenerators and nanopiezotronics are among the list of top 10 emerging technologies according to *New Scientist* and *MIT Technology Review* [12,13].

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