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Piezoelectric Nanowire toward Harvesting Energy from In-Vivo Environment

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Abstract

This paper discusses technologies used to harvest energies from in-vivo environment. The discussion mainly concentrated on nanogenerators based on Piezoelectric nanowires which are employed for converting biomechanical energy (such as muscle stretching), vibration energy (such as heart rate sound, sound waves) and biohydraulic energy (such as blood flow, contraction of blood vessel) into electric energy. At the end this paper studies an approach for harvesting biomechanical and biochemical energies from living organisms simultaneously. This system, by using aligned nanowire arrays, can power medical nanosystems and nanodevices through converting vibration, biomechanical and biohydrulic energies into electricity. On the other hand by using biofuel cell structure, this hybrid cell can convert biochemical (glucose/O_2) energy in biofluid into electricity. This technology can provide adequate power required for feeding nanodevices and nanosystems or at least to indirectly charge battery of the device. This technology can provide a sound basis for designing wireless self-powered nanodevices with direct energy harvesting from in-vivo environment.

Keywords*: in-vivo environment, Piezoelectric nanowire, nanogenerator, self powered nanosystem*

1. Introduction

Exploring renewable, sustainable and green energy resources is the most critical challenge to sustainable development of human civilization [1]. Today active research and development are being taken in exploring alternative energy resources such as solar, geothermal, biomass, nuclear, wind, and hydrogen. In nanotechnology, from one hand there is a wide distance between energy resources and available technologies and on the other hand there is an urgent need for independent and continuous operations in building and designing of implantable biosensors, ultrasensitive chemicals and biomolecular sensors and nanorobotics. For example an implanted wireless biosensor, includes a power source, which may be provided directly or indirectly by charging a battery. We know that changing the battery of such systems is very difficult and expensive and in some cases very dangerous. Therefore developing nanotechnology that harvests energy from the environment without using battery to self-power these nanodevices is a key advantage of self powered nanosystems [2]. A key advantage of nanodevices and nanosystems is that they usually operate at a very low power in the range from nW to μW. So the energy harvested from the environment can be enough to power the system. Scientists are trying to provide energy for mobile and wireless microelectronics using thermoelectric, mechanical vibration, and piezoelectric (PZ) vibration [3]. A human body provides numerous potential power sources including biomechanical energy, vibration energy, chemical energy (glucose), and hydraulic energy. If a small fraction of such energy could be converted into electricity, the energy may be sufficient to power small devices for biomedical devices [4].

In this paper first we consider how electricity is produced by piezoelectric nanowires-exclusively ZnO- and then we introduce approaches for producing electricity from human body by using Zn oxide nanostructures.

2. Piezoelectric Nanowire Based Nanogenerator

Researchers in nanotechnology science are presenting innovative nanotechnologies for converting mechanical energy (such as body movement, muscle stretching), vibration energy

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(such as acoustic/ultrasonic wave), and hydraulic energy (such as body fluid and blood flow) into electric energy so that they can power nanodevices without using battery [5]. Some studies based on aligned ZnO nanowires (NWs) grown on a conductive solid substrate are done. Why ZnO? ZnO is a material that can get compatible with the live environment so it can be used for energy harvesting from live bodies [6]. The measurements were performed by an atomic force microscope (AFM) using a Si tip coated with Pt film. When the AFM is in contact, a constant normal force of 5nN was maintained between the tip and sample surface (Figure 2a). The tip scanned over the top of the ZnO NW, and the tip's height was adjusted according to the surface morphology and local contacting force. In the corresponding voltage output image for each contact position, many sharp output peaks were observed (Figure 2b).

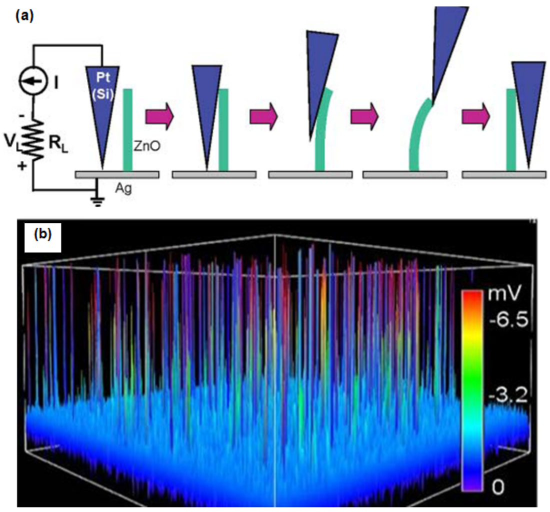

Figure 2. (a): Experimental setup and procedures for generating electricity by deforming a PZ NW with a conductive AFM tip. The base of the NW is grounded and an external load of RL is applied. The AFM scans across the NW arrays in contact mode. (b) Corresponding output voltage image of the NW arrays [7].

The physical principle for creating, separating, and preserving the piezoelectric charges in the NW is a mixture of piezoelectric and semiconducting properties [7]. The principle of this design is based on a piezoelectric property which is the ability of some special crystals to produce a voltage in response to applied stress. When the gravity force pulls the piezoelectric down, the upper layer of it gets stretched and the downside layer gets compressed. This leads to the formation of positive and negative voltage in these layers.

3. Piezoelectricity and Piezopotential

We now use ZnO to elaborate the structure and piezopotential in wurtzite family. Wurtzite crystal has a hexagonal structure with a large anisotropic property in c-axis direction and perpendicular to the c-axis. The crystal lacks of center symmetry, which is the core of piezoelectricity due to the intrinsic crystallographic structure. Simply, the Zn^{2+} cations and O^{2-} anions are tetrahedrally coordinated and the centers of the positive ions and negatives ions overlap with each other. Therefore, the crystal shows no polarization under strain-free condition. If a stress is applied at an apex of the tetrahedron, the center of the cations and the center of anions are relatively displaced, resulting in a dipole moment (Figure 1A). A constructive adds up of the dipole moments created by all of the units in the crystal results in a macroscopic potential drop along the straining direction in the crystal. This is the piezoelectric potential (piezopotential) (Figure 1B) [8]. The piezopotential, an inner potential in the crystal, is created by the non-mobile, non- annihilative ionic charges, the piezopotential remains in the crystal as long as the stress remains [9]. The magnitude of the piezopotential depends on the density of doping and the strain applied.

The distribution of piezopotential in a ZnO NW has been calculated using the Lippman theory [10]. For simplicity, we first ignore doping in ZnO so that it is assumed to be an insulator. For a one-end fixed free-standing NW that is transversely pushed by an external force, the stretched side and the compressed side surfaces exhibit positive and negative piezopotential (Figure 1B), respectively, which can act as a transverse voltage for gating the charge transport along the NW [11]. An alternative geometry is a simple two-end bonded single wire with a length of 1200nm and a hexagonal side length of 100nm [12]. When a stretching force of 85 nN is uniformly acting on the NW surfaces surrounded by electrodes in the direction parallel to c-axis, it creates a potential drop of approximately 0.4 V between the two end sides of the NW with the +c axis side of higher potential. When the applied force changes to a compressive, the piezoelectric potential reverses with the potential difference remaining 0.4 V but with the −c axis side at a higher potential.

The presence of the piezopotential in the crystal has created a few new research fields. A nanogenerator has been developed for converting mechanical energy into electricity [13]. Once a strained piezoelectric crystal is connected at its two polar ends to an external electric load, the piezopotential creates a drop in the Fermi levels at the two contact ends, thus, the free electrons in the external load are driven to flow from one side to the other to ‘‘screen’’ the local piezopotential and reach a new equilibrium. The generated current in the load is a result of the transient flow of electrons. An alternating flow of electrons is possible if the piezopotential is continuously changed by applying a dynamic stress across the crystal. This means that the nanogenerator gives continuous output power if the applied stress is varying, which means inputting mechanical work. The nanogenerator has been extensively developed and it is now gives an output of~3V, and the output power is able to drive a liquid crystal display (LCD), light emitting diode and laser diode [14]. The nanogenerator will play an important role in energy harvesting as the sustainable and self-sufficient power sources for the micro/nano-systems. We now introduce the electronic processes induced by the piezopotential in the next few sections.

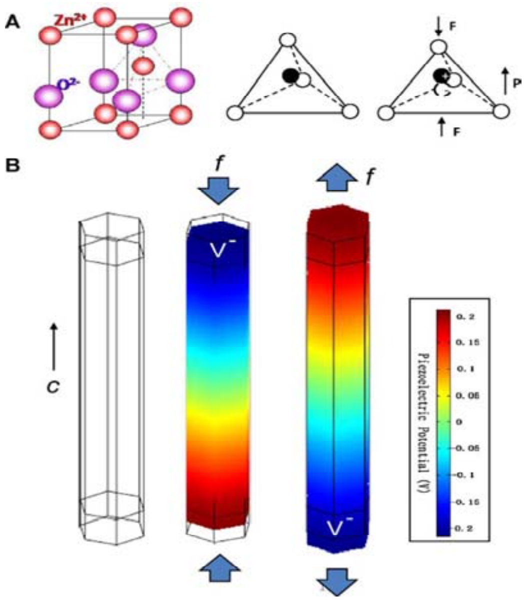

Figure 1. Piezopotential in wurtzite crystal. (A) Atomic model of the wurtzite-structured ZnO. (B) Numerical calculation of the piezoelectric potential distribution in a ZnO nanowire under axial strain. The growth direction of the nanowire is c-axis. The dimensions of the nanowire are L = 600nm and a = 25 nm; the external force is fy =80nN [9].

4. Nanogenerator Operation Principle in Converting Mechanical Stress to Electricity [15]

For a vertical, straight ZnO NW, the deflection of the NW by AFM tip creates a strain field, with the outer surface being tensile and inner surface compressive (Figure 3). Piezoelectric field E_z along the NW is then created. This field is closely parallel to the NW at the outer surface and anti-parallel to the NW at the inner surface .Hence, across the width of the NW, the electric potential distribution from the compressed to the stretched side surface is approximately between Vs^- (negative) to Vs^+ (positive) (figure 3a to 3d). We now consider the voltage output process. In the first step, the AFM conductive tip that induces the deformation is in contact with the tensile surface of positive potential Vs (Figure 3a). The Pt metal tip has a potential of nearly zero, (V_m = 0), so the metal tip ZnO interface is negatively biased for $\Delta V = V_m - V_s^- < 0$. With consideration the n-type semiconductor characteristic of the ZnO NWs, common level of NW and tip (M-S junction) interface in this case is a reverse-biased Schottky. A Schottky contact is a metal-semiconductor contact at which a potential barrier is formed, so that it behaves like a diode that only allows the current to flow from metal to semiconductor, and little current flows across the interface. In fact this process is a combination of creating, separating and accumulating the charges. In the second step, when the AFM tip is in contact with the compressed side of the NW (Figure 3f), the metal tip ZnO interface is positively biased for $\Delta V = V_m - V_s^+ > 0$. The M S interface in this case is a positively biased Schottky diode, and it produces a sudden increase in the output electric current. This voltage difference makes electrons flow from ZnO NW to the metal tip. This is called the charge releasing process. The mechanism shown here is in fact piezoelectric nanogenerator (NG) mechanism based on NW arrays.

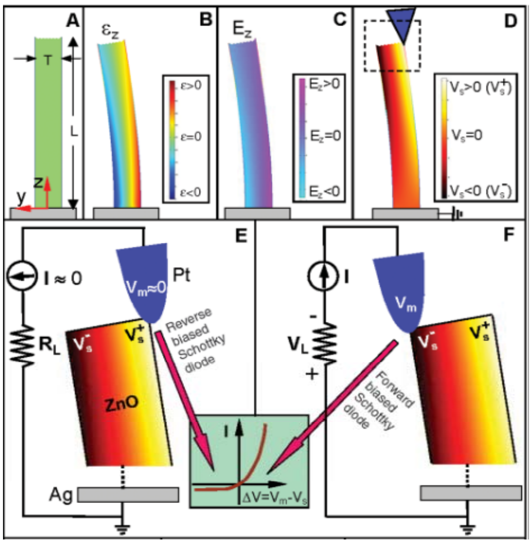

Figure 3. Principle of power generation in a ZnO NW. (a) Schematic of the NW and coordinate system. (b) Longitudinal strain ε_z distribution in the NW after deflection by an AFM tip from the side. Image shows a FEMLAB simulation for a ZnO NW of length 1 μm and aspect ratio of 10. (c) Corresponding longitudinal electric field E_z distribution in the NW induced by the piezoelectric effect. (d) Potential distribution in the NW. The dashed box indicates the area shown in parts (e) and (f). (e), (f) Interface between the metal AFM tip and semiconducting ZnO NW under local positive and negative contact potentials, showing reverse- and forward-biased Schottky rectifying behavior, respectively. This oppositely biased Schottky barrier across the NW makes it possible to preserve the piezoelectric charges and produce a voltage discharge output. Inset: typical I-V characteristic of a metal-semiconductor (n-type) Schottky barrier. The process in (e) builds up the potential; the process in (f) discharges the potential [16].

5. Converting Sound Waves into Electricity [17]

The experimental set up is schematically shown in (Figure 4a). This implement receives the vibration energy caused by environment sound waves and also mechanical stress and converts them into electricity. Sound waves in human body can include heart rate sound. This approach follows the same principles mentioned in previous part but with a small difference. As shown in Figure 4 (a) this sample includes an array of aligned ZnO NW and a zigzag Si electrode coated with pt. The Pt coating is not only for enhancing the conductivity of the electrode but also for creating a Schottky contact at the interface of electrode with NW. The top electrode is composed of parallel zigzag trenches fabricated on a (001) orientated Si wafer and coated with a thin layer of Pt film. These zigzag electrodes are placed above the NW arrays at a controlled distance and role as AFM tips. The electricity produced by the relative deflection/displacement between the NWs and the electrode via either bending or vibration is expected to be output simultaneously and continuously. Figure 4b shows how the electric current is generated by these nanogenerators.

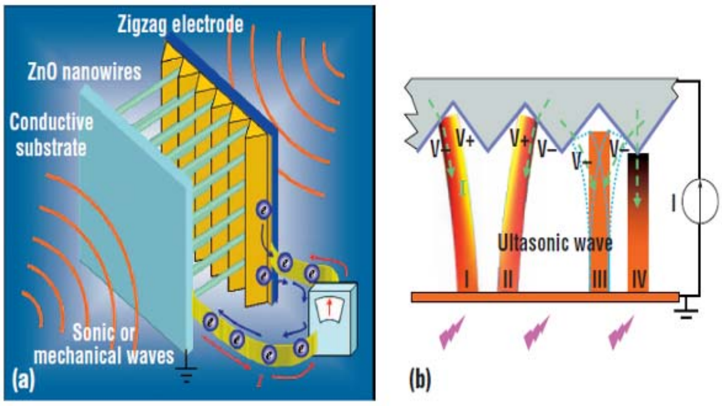

Figure 4. (a) Schematic diagram showing the direct current nanogenerator built using aligned ZnO NW arrays with a zigzag top electrode. An ultrasonic wave or mechanical vibration drives the nanogenerator, and the output current is continuous. (b) A schematic illustration of the zigzag electrode and its contact with the various NWs configurations and the resulting current [17].

6. Flexible Nanogenerators for Biomedical Energy Harvesting

To obtain the available energy in live creatures we need nanogenerators with flexible substrates. Semiconductor substrates used for growing ZnO NWs are hard and cannot be used in the areas that require flexible power source [18]. So in these environments it is necessary to use conductive polymer/plastics as biocompatible substrate. Flexible plastic substrates used for growing aligned ZnO NW arrays cause more accordance with body muscles so we can use from mechanical energy of the body (expansion and contraction of muscle and diaphragm) to produce electricity. One of the advantages of this approach is that we have multiple choices for flexible plastic substrates which play an important role in building portable, flexible electronics that are compatible with body of live creatures. The NG based on a single ZnO nanowire that is laterally bonded onto a polymer substrate was first demonstrated by a group of researchers [19]. Figure 6, shows energy harvesting by a SWG (figure 5) from breath and heart rate. These approaches by considering NG fiber bases, allows us to harvest energy from human body movements, muscle stretches and vibration [20]. The working principle of the PVDF NG is based on the insulating property of the PVDF NF and the creation of an inner piezoelectric field during applied tensile strain. As the device is deformed under alternating compressive and tensile force (Figure 7b), the NF acts like a “capacitor” and “charge pump”, which drives a flow of electrons back and forth through the external circuit. This charging and discharging process results in an ac power source. The output voltage is dictated by individual nanowire, while the output current is the sum of those from all of the active nanowires. The output of the PVDF NG could be improved by replacing PDMS with a material having a higher break-down voltage, because by that, higher poling fields could be applied to obtain a greater polarization which yields to obtaining higher output [21]. In addition, hundreds of NFs could potentially be integrated together and connected in series and/or parallel to improve the power output more.

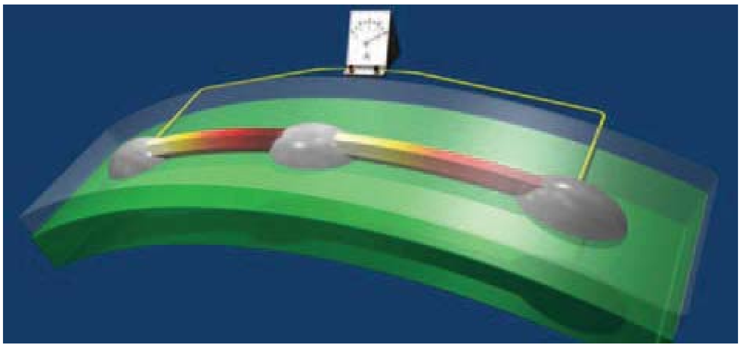

Figure 5. Schematic of the SWG [18]

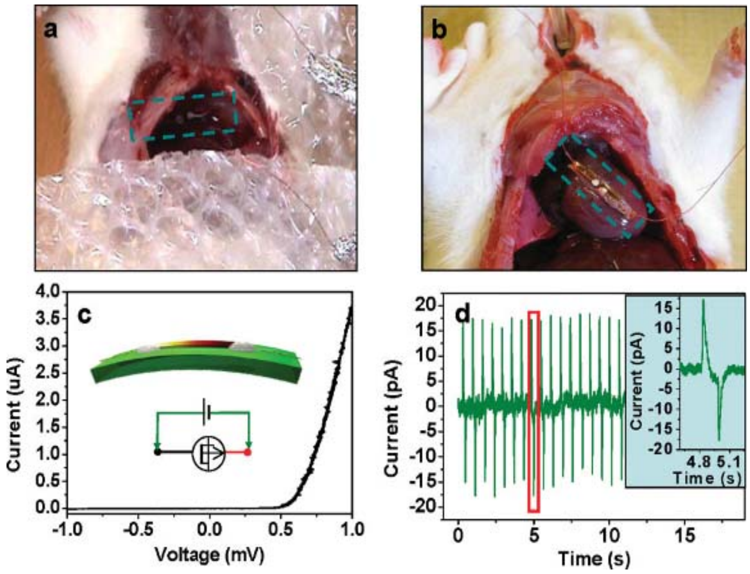

Figure 6. Energy harvesting from the breath and heart beat of a live rat using a SWG. a,b) A SWG attached to a live rat's diaphragm (a) and its heart (b), which drives the SWG to periodically bend and produce an AC power output. c) I–V characteristics of the SWG. The inset illustrates the schematic of the SWG and its connection configuration in reference to the measurement system. d) Typical current output recorded from a SWG under in vivo conditions [from the set-up in (a)] [20].

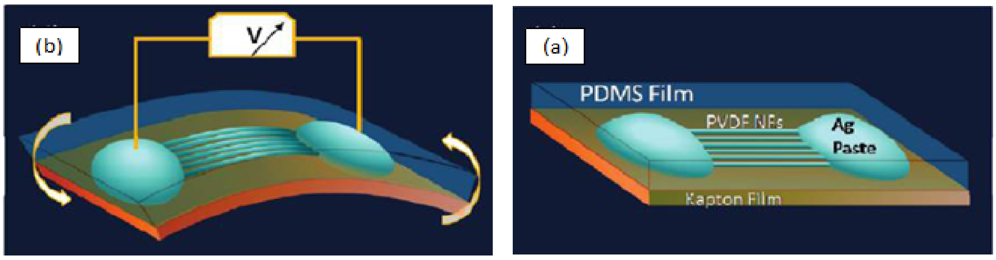

Figure 7. (a) The PVDF NF lies on a Kapton substrate, with both ends bonded with silver paste and the entire device encapsulated with PDMS. (b) Mechanical bending of the substrate creates tensile strain and a corresponding piezoelectric field along the fiber that drives the electrons through an external load back and forth following the cycled mechanical action [21].

7. Connection of Nanogenerator and Biofuel Cell for Harvesting Multi Kinds of Energy from Body Synchronously and Producing Electricity

In this part a hybrid device to power implantable equipments in the in vivo is introduced. This hybrid consists of PVDF NG and a bio fuel cell (BFC) [21]. To integrate the AC voltage of the PVDF NG with the DC voltage of the BFC, a simple RC high pass filter (Figure 8) was used, which effectively blocks the DC voltage of the BFC in one direction while passing the AC voltage of the NG. By integrating the two devices, the peak voltage was nearly doubled. In addition the kind of packaging of the PVDF NG should allow for operation inside biofluid and in-vivo environments. In addition, using a flexible Kapton film substrate for the BFC permits the devices to be integrated back-to-back. The power output of the hybrid nanogenerator is the sum of the BFC and NG powers. The voltage output of the BFC is V_{BFC} and the output voltage of the ac NG is $\pm V_{NG}$. Considering the infinitely large resistance of the PVDF nanofiber, the output voltage of the NG component is $\pm V_{NG}$ even with the presence of a load. The inner resistance of the BFC is rather low since it is dictated by electron transfer between the active center of the enzymes and the electrodes. In such a case, the voltage applied to an external load R is $V_{BFC} \pm V_{NG}$. The peak output power for each cycle is $((V_{BFC} \pm V_{NG})\ 2)/R$. Also, these methods can be used for the better rectification of ac nanogenerators and promoting dc output.

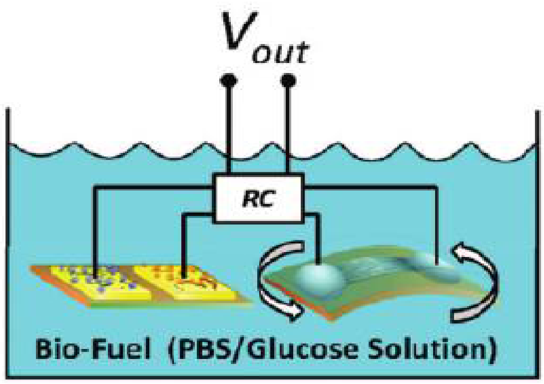

Figure 8. Schematic of biomechanical and biochemical hybrid energy harvester [21].

8. Conclusion

This paper considers new implements based on Piezoelectric nanowires for producing electricity from in-vivo environment.For medical nanosystems and nanodevices, the best approach is hybrid cell with the ability to harvest biomechanical and biochemical (glucose/O_2) energy simultaneously from the in-vivo environment. By using aligned nanowires this generator can convert vibration energy, biomechanical energy, biohydraulic energy and sound into electricity. On the other hand by using biofuell cell structure, this hybrid cell can convert biochemical (glucose/O_2) energy in biofluid into electricity. The high output power, low cost and easy fabrication process, large-scale manufacturability, high ‘on-chip’ integrability and stability demonstrates its great potential for in-vivo biosensing. These implements provide a new approach for self-powered nanotechnology that harvests electricity from the environment for applications such as implantable biomedical devices, wireless sensors, and even portable electronics that are important for biological sciences, environmental monitoring, defense technology and even personal electronics. This technology can provide adequate power required for feeding nanodevices or at least to indirectly charge battery of the device. This technology can provide a sound basis for designing wireless self-powered nanodevices with direct energy harvesting from the in-vivo environment.

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