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AN INTRODUCTION TO SELF-POWERED NANOSYSTEMS

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Abstract

This work presents a detailed interesting introduction about the importance and results of self-powered systems in studying nanostructures; piezoelectric sensors and piezotronics are also considered.

Keywords *Nanostructures, nanosystems, nanopiezotronics, piezoelectric sensors, self-powering*

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Introduction

The development of wireless nanodevices and nanosystems results nowadays in a critical importance for sensoristics (implantable bio-sensoristics, ultrasensitive chemical and molecular sensors), so as for the medical science, defense technologies, nano-robotics, micro- (nano)- opto- electro- mechanical (M(N)OEMS) systems, remote and mobile environmental sensors, portable and resistant personal electronics. It results highly desirable and required that the implantable biomedical devices are self-powered, i.e. without the use of batteries. For the growing global needs it has become essential in the recent years the exploration of innovative nanotechnologies for the conversion of mechanical energy (such as the body movements, the muscle stretching), vibrational energy (such as the acoustic and ultrasonic waves), hydraulic energy (such as the flow of body fluids), chemical energy (for example from glucose) into electrical energy, to be used for such batteries-free devices. These conditions have attracted a lot of scientists on the study, research and creation of self-powered nanosystems.

It has been shown a new approach [1] for converting mechanical energy into electrical energy by means of nanowires arrays of piezoelectric ZnO. The key mechanism of such generators is based on coupling of piezoelectric and semiconducting properties of nanowires/nanobelts (NWs/NBs) of ZnO with the presence of a Schottky barrier in the metal/semiconductor interface. Based on this mechanism, there have been developed nanogenerators driven by ultrasonic waves, operating also in fluid substances (for example in a bio-fluid).

In great development there is also a recent field of study, called “nanopiezotronics”, which utilizes the coupling of piezoelectric and semiconductive properties for the manufacture of new devices and electronic components, such as the piezoelectric field effect transistors (PEFETs), the piezoelectric diodes (PE diodes) and sensors.

With the problem of the energetic crisis and the global pollution, the research of “green” and renewable energetic resources is one of the most urgent challenges to the sustainable development of the human civilization. At great scale, besides the known energetic resources of the actual world, as oil, coal, hydroelectric energy, natural gas, nuclear energy, alternatives energetic resources are being explored, as solar energy, geothermal energy, biomasses, eolian energy, the hydrogen.

The research involves the integration of multifunctional nanodevices in a nanosystem, so that it can work in a way possibly similar to a living kind, i.e. with sensorial, control, communication and answer/action abilities. Such nanosystem is composed not only of nanodevices, but also of nanobatteries [2]; the small dimensions of such power sources limit considerably their lifetime. It results therefore its great importance for the development of a nanotechnology able to harvest energy from the environment for such self-powered nanodevices. For all these reasons, one of the challenges of actual nanotechnology is therefore the construction of such ultrasmall, ultrasensitive, extraordinarily multifunctional systems and at low energy consumption, which, harvested by the environment, results sufficient for making workable these systems. Various approaches for harvesting energy have been developed, in relation to mobile and wireless microelectronics, through the use of thermoelectric, mechanical and piezoelectric vibrations [3]. The human body offers various potential sources of energy (mechanical, vibrational, chemical, hydraulic energy). If a fraction of such energy can be converted in electricity, it results sufficient to power small devices for a great variety of purposes (Fig. 1).

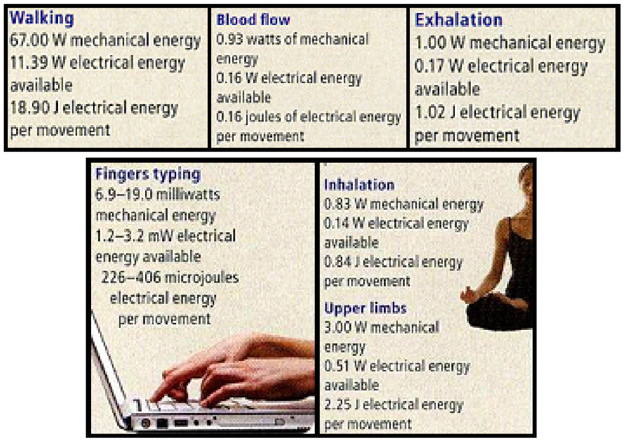

Figure 1: *The amount of energy produced by the human body in the indicated situations [1].*

The piezoelectric Nanogenerator

The typical piezoelectric nanogenerator is based on ZnO nanowires and has the following experimental features:

1) the output potential gives a sharp peak, which is negative with respect to the ground of the nanowire;

2) there is no output current when the tip of an AFM microscope (normally used for the longitudinal deflection of the nanowires, determining in this way a longitudinal distribution of strength) first touches the nanowire and pushes it; an electrical output is observed only when the tip of the AFM is leaving the nanowire at the second half of the contact;

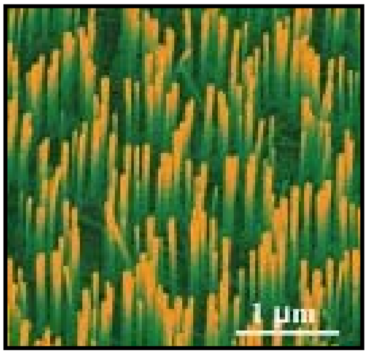

Figure 2: *SEM image of aligned ZnO nanowires, grown on a substrate of GaN/sapphire [6].*

Tabel 1 (A): *Results for resistance, voltage and discharge current related to the study on ZnO and TiO_2 nanogenerators.*

Properties	ZnO [7]	TiO_2 [7]	ZnO [8]
Resistance (Ω)	$3x10^3$	$3x10^3$ - $1.5x10^6$	$3.5x10^3$
Voltage (V)	$3.3x10^{-3}$	$5.5x10^{-2}$	$\sim10^{-3}$
$I_{discharge}$ (A)	10^{-6}	$3.6x10^{-8}$	10^{-9}

Tabel 1 (B): *Other interesting results related to the study on ZnO and TiO_2 nanogenerators.*

Properties	ZnO [7]	TiO_2 [7]	ZnO [8]
Number of nanostructures	10^7	10^9	250-1000
P_{max} (W)	$3x10^{-9}$	$2x10^{-9}$	10^{-12}
Area (cm^2)	1	10	$2x10^{-2}$
Density (/μm^2)	30	10^3	10
Height (nm)	200	5	10^3
Diameter (nm)	200	30	40

3) it has output power only when the tip touches the compressed part of the nanowire;

4) it is observed an output signal only for piezoelectric nanowires. There is no output current if the nanowires

are of tungsten oxide, carbon, silicon or metal nanotubes. The potential of friction or contact is not involved in the observed power output;

5) the intensity of the output signal depends very strongly on the size of nanowires;

6) for having on fact output electricity, the contact between the tip and the nanowire must have Schottky nature and the contact between the nanowire and the ground must be ohmic-type [4,5] (Fig. 2) (Tab. 1 (A), (B)).

Nanopiezotronics

The concept of nanopiezotronics was introduced in 2006 and its definition and detailed description were published in the following year. The ground of nanopiezotronics regards the use of coupled piezoelectric and semiconductive properties of nanowires and nanobelts for designing and fabricating devices and electronic components; the transport properties of the controlled piezoelectric field are used for the realization of unique and new electronic components, such as PE-PETs and PE diodes. The new electronic devices, based on these properties, are sensitive and well-controlled by external applied forces as a pressure. As exemplification, few notes on the field effect piezoelectric transistors and piezoelectric diodes will be further presented.

The field effect piezoelectric transistor utilizes a single nanowire (or nanobelt) of ZnO. The physical principle at the basis of the process involves the piezoelectric potential, which is created in the nanowire through its bending; this has the function of gate of a conventional field effect transistor. The contacts at both ends are ohmic-type. Differentiating the bending of the nanowire, it is possible to get different I-V characteristics (Fig. 3).

The characteristic piezoelectric diode is constituted by a nanowire with an end fixed to a metal electrode, while the other end can be bent through a mobile metal tip. Both ends have ohmic contact with ZnO.

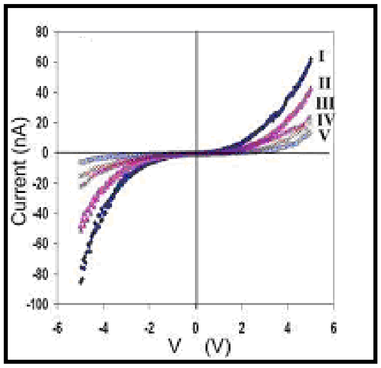

Figure 3: *Examples of the I-V characteristics of a nanowire of ZnO for five different cases of bending [6].*

By varying the angle of bending there are corresponding I-V characteristics (Fig. 4).

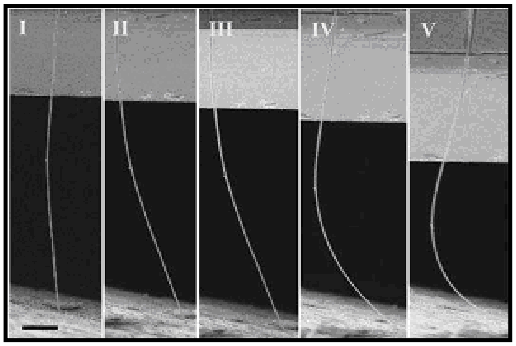

Figure 4: *SEM image of five different cases of bending of a ZnO nanowire. The indicated scale bar represents 10 μm [6].*

Piezoelectric Sensors

The stress sensors based on piezoelectric fine ZnO wires (PFWs) are manufactured with a relatively simple, reliable and low-cost technique. The electromechanical sensor device consists of a single nanowire electrically connected, placed on the outer surface of a flexible substrate of polystyrene (PS), bound at its two ends. The entire device is totally inserted in a thin layer of polydimethylsiloxane (PDMS). The nanowire has Schottky contacts at both ends, but with different barrier heights (Fig. 5). The I-V characteristic is highly sensitive to stress, mainly due to the change in the height of the Schottky barrier (SBH), which depends linearly from the strain. It is the combined effect of change of band structure induced by stress and piezoelectricity that leads to a change of height of the barrier.

This typology of sensors has applications in measuring of stress and strains in cell biology, biomedical sciences, MEMS devices, structures monitoring, and more. The nanostructures of one-dimensional ZnO, as nanowires and nanobelts, are considered very important as basic elements for the manufacture of various nanodevices, not only in the nanosensoristic sector.

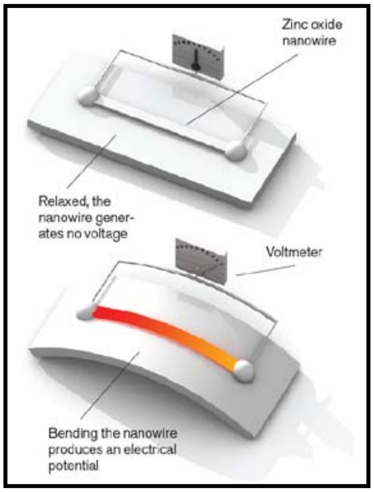

Figure 5: *Schematization of a bend sensor device, based on a single thin nanowire ZnO [9].*

Considering the extreme smallness of the diameter of the PFW in comparison with the thickness of the substrate of PS, the axial stress ε_{zz} along the length of the PFW is approximately [10]:

$$\varepsilon_{zz} = 3\frac{a}{l}\frac{D_{\max}}{l}\left(1-\frac{z}{l}\right) \qquad (1)$$

where z is vertical distance measured from the fixed part to the substrate of PS until the center of the PFW, a is the half-thickness of the PS substrate, l the length of the PS film from the fixed side to the free one and $D_{\max}$ the maximum deformation of the free part of the PS substrate, with positive or negative sign depending on compressive stress or tension of the PFW respectively.

The relation (1) states that the stress ε_{zz} is connected in linear way with the maximum deformation $D_{\max}$. On fact, since the length of the substrate is much greater than the length of the PFW ($l >> L$), the stress in the PFW is with good approximation uniform (Fig. 6).

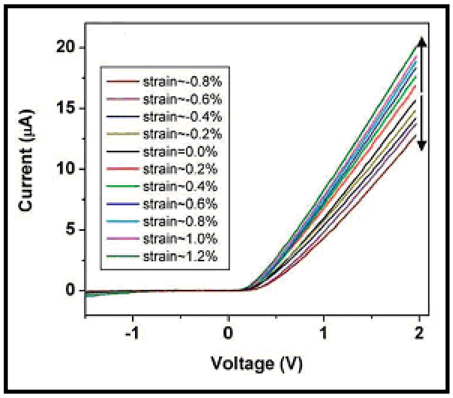

Figure 6: *Typical I-V characteristics of a sensor with the indicated peculiarities, subjected to various stresses [11].*

Considering the classical theory of thermoionic emission-diffusion, assuming that T is independent from the stress for small deformations, the inverse Schottky barrier Φ_S can, in principle, be derived from the logarithm of the current. Consequently, the change of SBH can be determined by:

$$\ln\frac{I(\varepsilon_{zz})}{I(0)} = -\frac{\Delta\Phi_S}{KT} \qquad (2)$$

with $I(\varepsilon_{zz})$ and $I(0)$ respectively measured current through the PFW at a fixed inclination, with and without stress. The effect of the piezoelectric polarization on the Schottky barrier height occurs because of fact that the polarization produces surface charges at the interface, where the divergence of the polarization is different from zero, i.e. in the metal-semiconductor interface and below the region of exhaustion of the semiconductor.

These fully packaged strain sensors, based on a single PFW of ZnO, have high stability, fast response and a high calibration factor. The characteristic I-V curve is modulated by the change of the Schottky barrier height, which has a linear-type relation with the stress.

The underlying mechanism for the change of such height is attributed to the combination of band structure change induced by stress and the piezoelectric effect. Such combination of effects (piezoelectric and semiconductive effects) is also known as piezotronic effect [12].

The sensors built with these characteristics have important applications in measures of stresses in cell biology, biomedical sciences, MEMS devices, structure monitoring and earthquake monitoring.

Conclusions

The future nanotechnological research will certainly still focus efforts on the areas related to the integration of individual nanodevices in a nanosystem acting similarly toliving species, i.e. with sensorial, communication, control and response abilities. A nanosystem requires a nanoscaled power source, able to preserve the reduced dimensions of the entire device and working with high performance. One of the ultimate goals could be the realization and optimization of self-powered nanosystems, able to work wireless [13].

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