Nanopiezotronics in Biological and Medical Field

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ABSTRACT

A new research field, nanopiezotronics refers to generation of electrical energy at nanometer scale through mechanical stress to the nanopiezotronic device. This is the new approach of the potential of converting biological mechanical energy, acoustic/ultrasonic vibration energy, and bio fluid hydraulic energy into electricity, representing a new way for self-powering of wireless nanodevices and nanosystems. Nanopiezoelectronic devices include nanowires, nanogenerators, sensors and transistors are playing crucial role in nanoscience and biotechnology as well as biomedical applications. The perspectives of the potential applications of the silicon nanowires for biodetection and drug delivery are very crucial to the biomedical field. Thus, the concept of "nanopiezoelectronics" is introduced as a set of approaches to engineer the nanowires and nanodevices/ nanosensors and to enrich their functionality and potential applications in nanoscience and biotechnology for the upcoming future.

Keywords: Nanopiezotronics, nanodevices, biodetection, drug delivery and biomedical field

INTRODUCTION

Piezoelectricity is a coupling between a material's mechanical and electrical behavior. When a piezoelectric material is squeezed, twisted, or bent, electric charges collect on its surfaces. Whenever a piezoelectric material undergoes a voltage drop, mechanical deforms occur. Generally crystalline materials show piezoelectric behavior and wheneversimilar crystal is deformed mechanically, the positive- and negative-charge centers are displaced with respect to each other. Hence, when the overall crystal is electrically neutral, the difference in charge center displacements results in an electric polarization within the crystal. Electric polarization resulting from mechanical deformation is perceived as piezoelectricity.

A new research field, nanopiezotronics refers to generation of electrical energy at nanometer scale through mechanical stress to the nanopiezotronic device. As for instance, bending of a zinc oxide nanowire changes the mechanical energy into electrical energy. This is the new approach of the potential of converting biological mechanical energy, acoustic/ultrasonic vibration energy, and bio fluid hydraulic energy into electricity, representing a new way for self-powering of wireless nanodevices and nanosystems.

HISTORY OF NANOPIEZOTRONICS

The term "nanopiezotronics" was coined by Professor Zhong Lin Wang at Georgia Tech to explain the coupled piezoelectric and semiconducting property of nanowires and nanobelts for designing and developing novel electronic devices like nanotransistors and nanodiodes. These may provide the fundamental building blocks that would allow the creation of a new area of nanoelectronics.

The mechanism of nanopiezotronic uses the advantage of the fundamental property of nanowires or nanobelts made from piezoelectric materials which includes bending the structures that creates a charge separation. The positivecharge is on one side and negative on the other. The link between bending and charge creation was been used to create nano-generators that produces measurable electrical currents when an array of zinc oxide nanowires is bent and then released. (1)

BASIC STRUCTURE OF NANOPIEZOTRONICS

The basic structure of nano- piezotronics is as follows:

A semiconducting device includes a substrate, a piezoelectric wire, a structure, a first electrode and a second electrode. The piezoelectric wire has a first end and an opposite second end and is disposed on the substrate. The structure causes the piezoelectric wire to bend in a predetermined manner between the first end and the second end so that the piezoelectric wire enters a first semiconducting state. The first electrode is coupled to the first end and the second electrode is coupled to the second end so that whenever the piezoelectric wire is in the first semiconducting state, an electrical characteristic will be exhibited between the first electrode and the second electrode.(2)

THE NEW FIELD OF NANOPIEZOTRONICS

Semiconducting and piezoelectric nanowires and nanobelts have exciting applications in electronics, optoelectronics, and sensors and especially in biological sciences. Semiconducting oxide are a unique group of quasi-one-dimensional nanomaterials, which have been systematically studied for a wide range of materials with distinct chemical compositions and crystallographic structures. (3)

Among transparent conducting oxides, ZnO is probably the most commonly studied material as it has the following unique merits:

[1]. ZnO is a wide-band gap semiconductor that has huge potential for electronic, optoelectronic, and optical applications.

[2]. It is unique in having semiconducting, piezoelectric, and pyroelectric properties, and is an ideal candidate for fabricating electromechanical coupled devices.

[3]. ZnO is a biodegradable and possibly biocompatible material suitable for medical and biological applications.

[4]. ZnO nanostructures, such as dots, wires and belts, can be easily formed using either a chemical approach at low temperature (70°C) or physical methods at high temperature (500-600°C) over a wide range of substrates. (4)

APPLICATIONS OF NANOPIEZOELECTRONICS IN BIOLOGICAL AND MEDICAL FIELD

A) *Nanowires (Nw)*

Manufacturing

Synthesis of aligned arrays of NWs with controlled structures over large areas is an important step toward nano-manufacturing than fabrication of nanoscaled devices. Reproducible synthesis of NWs over a large surface area at high yield is also an important factor of NW manufacturing. (5,6)

ZnO NWs have been grown on polymer substrate or a solid-state using Au_{10} and Sn_{11} as catalysts. In the vapor-liquid-solid (VLS) growth method, the catalyst initiates and guides the growth and the epitaxial relationship between the NWs and the substrate leads to the aligned growth. A self-assembly based mask technique is combined with the epitaxial approach to grow large-area hexagonal arrays of aligned ZnO NWs. (7-9)

The aligning quality is controlled by-

i. the chamber pressure
ii. the oxygen partial pressure
iii. the thickness of the catalyst layer

Applications

1. As sensors for medicine and life sciences: The tuneable and reproducible conducting property of nanowires in combination with surface binding provides powerful approach to nanomedicine. Nanowires enable sensing and detection ability.[10]
2. Penetrating living cells using semiconductor nanowires. Kim et al [11] demonstrated that the Si nanowires were first prepared with a standard Si substrate having a density so that there were 20–30 nanowires within the diameter of a typical cell. They were vertically aligned Si nanowires and were approximately 6 mm long having a diameter of 90 nm. Mouse embryonic stem cells were cultured on these substrates and penetrated by the Si nanowires within approximately 1 hour as they settled on to the substrate without the application of external force. The cells were survived by this process provided the Si nanowire diameter was small compared with the cell size. By depositing DNA onto the wires, the researchers were also able to transfer the genetic material into human embryonic kidney cells. The team members were expected that the delivery efficiency could be improved by adjusting the surface chemistry of the nanowires. The nanowire arrays could be used for drug delivery applications or for electrical stimulation and detection in cells.[12-13]
3. Nanowires in the field of nanodetection and nanomedicine
4. Microbial nanowires for bioenergy applications: Metal-like conductivity of nanowires is a novel concept in bio-electron transport. Microbial nanowires play a role in multiple forms of extracellular electron transfer. Nanowires can facilitate interspecies electron transfer in methanogenic digesters. Increasing nanowire production enhances current densities in microbial fuel cells.[14]
5. Nanowires as future diagonostic tools for detection of cancer cells.[15]

B) Piezoelectric Nanogenerator

Piezoelectric nanogenerators can convert the kinetic energy of the heart to electric energy during the contractions and relaxations of the muscles. The output voltage is generally stable in three positions on the surface of the heart. The highest voltage appears on the surface of right ventricle, near atrioventricular groove, parallel to the long axis direction of the heart, which will be the potential new energy source for pacemakers. Piezoelectric nanogenerator can be used as cardiac function monitor in the future for its voltage output is positively correlated with myocardial contractile force. [16]

C) Nanowire Piezoelectric Nanogenerators On Plastic Substrates as Flexible Power Sources for Nanodevices

The ceramic or semiconductor substrates used for growing ZnO NWs are hard, brittle, and could be used in areas that require a foldable or flexible power source, such as implanted biosensors in muscles or joints, or power generators built into shoes [17]. It is necessary instead to use conductive polymer/plastics as substrates that are also likely to be biocompatible and biodegradable.

Two advantages are offered by this approach.

1. The large-scale solution method used to grow ZnO NW arrays at a temperature <80°C would be more cost effective.
2. The large choice of available flexible plastic substrates for growing aligned ZnO NW arrays.

D) Piezoelectric Field Effect Transistor

Field-effect transistors (FETs) based on NWs and nanotubes are some of the most frequently studied nanodevices. A typical NW FET is composed of a semiconducting NW connected at the ends by two electrodes and placed on a Si substrate covered by a thin layer of oxide. The Si substrate can be used as the gate electrode or a third electrode can be built on the top or bottom of the NW. The signal output from the drain electrode of the NW is controlled by a gate voltage applied between the gate and the NW. [(18)]

By connecting a ZnO NW across two electrodes that can apply a bending force to the NW, the piezoelectric field created across the bent NW serves as the gate for controlling the electric current flowing through the NW. This piezoelectric FET can be considered as a new type of transistor that is turned on/off by applying a mechanical force. As a result, it can act as a force sensor capable of measuring forces in the nano Newton range and smaller. [(19)]

E) Piezoelectric Resonator

Bulk acoustic resonators (BARs) are important devices for communication systems. They consist of a thin piezoelectric film sandwiched between two electrodes. A radio-frequency signal applied across the thickness of the film produces mechanical motion, and the fundamental resonance occurs when the film thickness equals half of the wavelength of the input signal.

Piezoelectric ZnO NBs can be effective piezoelectric resonators because of their high uniformity and dislocation-free structure.

HOW NANOPIEZOTRONICS CAN BE USEFUL IN BIOMEDICAL FIELD [(20)]:

1) Nanopiezoelectronic wires
   They could be useful in detecting molecular signs of disease in the blood, minute amounts of poisonous gases in the air, and trace contaminants in food.
2) Nanogenerator
   The nanogenerator could be embedded in clothing and used to convert the rustling of fabric into current to power portable devices such as cell phones.
3) Hearing aid
   An array of vertically aligned piezoelectric nanowires could serve as a hearing aid.
4) Signature verification
   A grid of piezoelectric wires underneath a signature pad would record the pattern of pressure applied by each person signing. Combined with a database of such patterns, the system could authenticate signatures.
5) Bone- loss monitor
   A mesh of piezoelectric nanowires could monitor mechanical strain indicative of bone loss.

CONCLUSION

There is a synergy between biochemistry, material science and medicine which led to a tremendous scientific progress in the fields of biodetection and nanomedicines in the last decade. This strongbond led to the emergence of a novel class of bioinspired systems which are based upon utilizing nanomaterials such as nanoparticles, carbon nanotubes, or nanowires, nanogenerators or as transducers for producing novel sensor devices, or sophisticated drug delivery agents. The developments made in the area of silicon nanowire-based devices and their applications in the diverse areas of nano and biotechnologies are very vast and interesting approach. Moreover, there is a complex interactions of organic species with nanoscale matter which is needed for sophisticated integration and packaging of the subsystems on a single chip. Finally, the perspectives of the potential applications of the silicon nanowires for biodetection and drug delivery are very crucial to the biomedical field. Thus, the concept of “nanopiezoelectronics” is introduced as a set of approaches to engineer the nanowires and nanodevices/ nanosensors and to enrich their functionality and potential applications in nanoscience and biotechnology for the upcoming future.

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