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Hybrid resonant energy harvester integrating ZnO NWs with MEMS for enabling zero-power wireless sensor nodes

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A B S T R A C T

This work introduces a novel concept for energy scavenging from ambient vibrations utilizing ZnO nanowires (NWs). This concept relies on the combination into a single device of a resonant element (i.e. an inertial mass suspended by four serpentine springs) and two arrays of NWs grown at both sides of the inertial mass. The NWs can be bent as a result of the resonant motion of the mass. Due to the zigzag-shaped profile of the inertial mass, this bending generates an electric current between the electrodes. This power can be used to supply wireless sensor nodes at the micro and nanoscale level. In addition, this generator can be integrated with other elements that can be achieved by taking advantage of the ZnO NWs and their unique properties such as chemical sensors, optoelectromechanical systems or logic circuits driven by mechanical or optical signals. A detailed fabrication process, containing the NW growth method, is described in this paper. Theoretical calculations and FEM simulations have been performed and show the possibility of using these kinds of devices to scavenge energy from sonic and ultrasonic waves.

1. Introduction

The invention of the bipolar transistor in 1947 was the first step toward modern electronics. Since then, seeking smaller and more powerful smart devices has been a worldwide topic of interest. The miniaturization of electronic systems reached unthinkable limits several decades ago [11]. Today, it is extremely common to find an integrated circuit with millions of transistors in devices used in our everyday lives.

Combined with the boom of wireless communications, the integration of miniature smart devices with sensing capabilities and wireless features is becoming a research hot topic. By adding a large number of wireless sensor nodes, an intelligent ambient known as a wireless sensor network (WSN), can be created. Although centimeter-scale smart devices are already around us, the rising challenge is to reduce their sizes in order to locate this type of device virtually everywhere. However, the miniaturization of the node, and consequently of the energy storage element, has a direct impact on the node lifetime. This limits the feasibility of this device because of the difficulty in recharging or replacing large numbers of devices and due, at times, to their unreachable locations. In order to overcome this difficulty, the concept of energy harvesting was created [13]. It claims the use of energy presenting at the immediate ambient to power the WSN node. These energy sources can have a thermal, light or mechanical nature. Mechanical vibrations [12,7] are particularly interesting because of the important power density and the nearly universal spatial and temporal availability.

There is an increasing volume of research showing energy scavenging devices at different scales. Depending on their transduction methods, it is possible to find piezoelectric, electromagnetic, electrostatic types [14,6,10]. The

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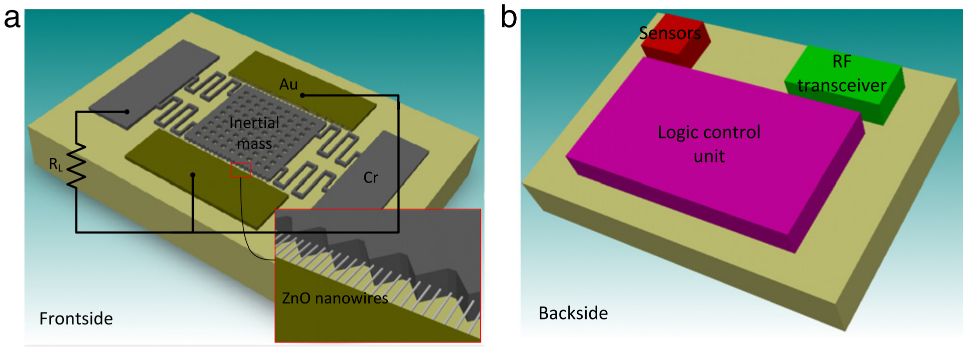

Fig. 1. Front-side of fabricated final device connected to a load resistor (a) and conceptual diagram of the die back-side showing an integrated autonomous wireless sensor node (b). Inset in (a): details of the horizontally grown ZnO NWs.

piezoelectric transduction is especially attractive because of its immediate alternate current output when the piezoelectric material is mechanically stressed. Previous literature shows everything from off-the-shelf mesoscale devices [3,4,1,2] to functional microscale prototype [14,8,5] and generators based on nanowires (NWs) [16–18,20]. While the microscale devices normally consist of a spring–mass system that converts vibrations into electricity using the system's resonance frequency, most of NW-based generators are formed by arrays of NWs placed between two electrodes and are bent by the direct effect of the excitation force.

Although a single NW strained by a tiny force of 5 nN can only scavenge around 0.05 fJ of energy [16], the integration of thousands or millions of these nanostructures can enhance the power output to fulfill the application requirements [17]. Alternatively, by using a resonant element, the amplitude of motion can be enhanced if the force has a harmonic nature. In this manner, the combination of these two ideas can be a new concept in the field of energy harvesting. The size of the resonator, i.e. inertial mass and suspension dimensions, will determine the operation frequency, and the size and spatial density of NWs, will determine the transduction throughput.

2. Fundamental of operation

ZnO has become a hot topic in material science over last few years. It is due to its wonderful properties that are difficult to find in nature in one single material. It was exploited as photonic material because of its direct bandgap of 3.37 eV that can result in the generation/absorption of UV light. It is possible to grow a wide variety of nanostructures utilizing this material, and it has the dual property of being both a semiconductive and piezoelectric material. One of the most useful nanostructures that can be utilized to generate energy is the NW. The ZnO NW can grow from different substrates, even though a crystalline material with a similar lattice constant is the best choice in order to obtain aligned and high-quality NWs. Additionally, in order to catalyze the growth of the NW, a seed material, such as a gold or ZnO layer, has to be used.

As mentioned above, this approach aims to link the NW-based generator invented by Dr. Wang's group and the typical vibration-driven resonant energy harvester. So the mechanical fundamentals of this generator lie in the typical working principle of a damped spring–mass system that can mechanically store part of the energy coming from an external vibration. When an ambient vibration actuates over the resonator at the resonant mode frequencies, the inertial mass will move with enhanced amplitude. This motion can be used to strain an array of NW that will surround the movable mass. Therefore the piezoelectric transduction force, which is generated over the movable mass by means of the sweeping of NWs arrays, converts the friction into electricity by using the same concept used in the zigzag-electrode nanogenerator (NG) [17]. In order to reproduce the same approach a zigzag profile is proposed for the inertial mass as seen in Fig. 1(a). The same configuration of creating a Schottky contact with one gold electrode and an Ohmic contact with a second chromium electrode is used here.

This generator can be integrated with other elements in order to assemble a WSN node (Fig. 1(b)). In addition, it can be use ZnO NWs and their unique properties to fabricate the rest of elements (i.e. chemical sensors, optoelectromechanical systems, logic circuits driven by mechanical or optical signal, . . .).

3. Fabrication of the energy scavenger

3.1. NW growth method

Among the different approaches for growing NWs, the hydrothermal chemical approach is the most convenient for our purpose. The main reasons are its synthesis simplicity, the low-temperature of this process and the possibility of varying the density and features of the grown NWs by changing the chemical reaction parameters.

ZnO synthesis can also be carried out on substrates such as ZnO, Au, Ag, and Pt. In order to achieve NW growth, thin films of these materials can be deposited onto different substrates, e.g. silicon, polymers, fibers, etc. Special care has to be taken due to the surface roughness of the thin film to promote nucleation. Usually, zinc nitrate hexahydrate and hexamethylenetetramine are used as chemical agents for the hydrothermal synthesis of ZnO NWs. In general, precursor concentration and type of seed layer determine the NW density, whereas growth time and