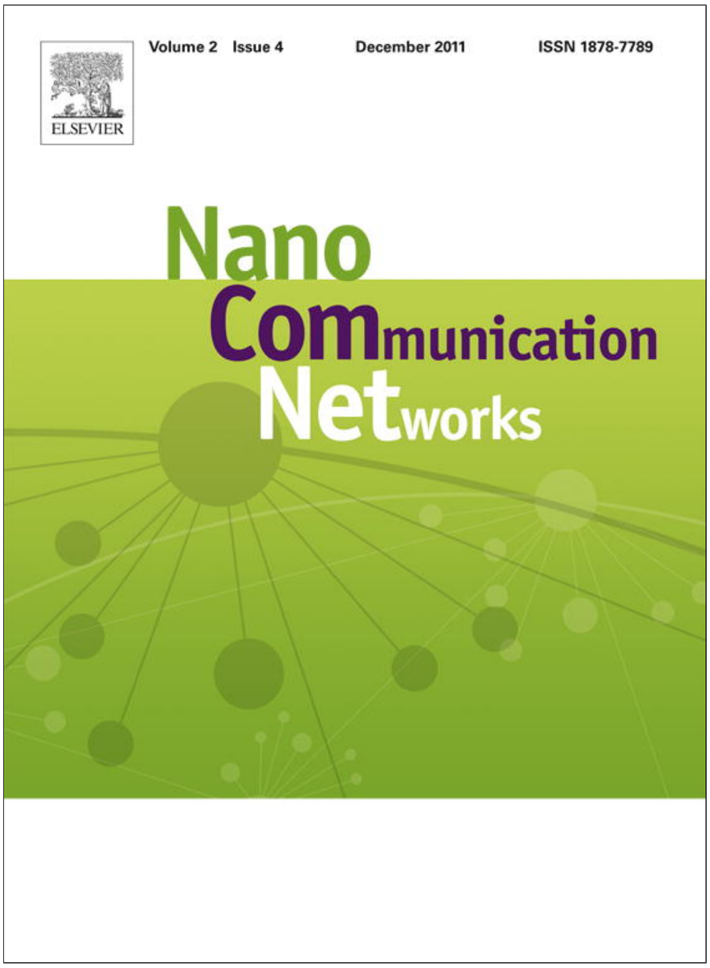
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Hybrid resonant energy harvester integrating ZnO NWs with MEMS for enabling zero-power wireless sensor nodes

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ABSTRACT

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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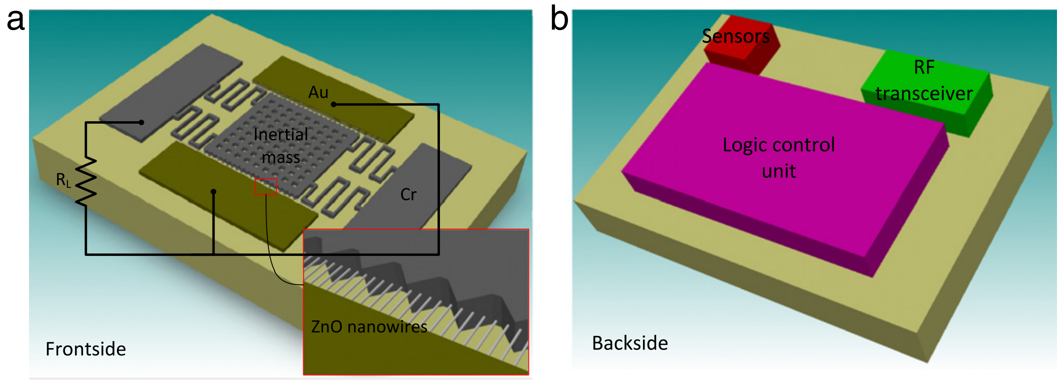

Fig. 1. Front-side of fabricated final device connected to a load resistor (a) and conceptual diagram of the die back-side showing an integrated autonomous wireless sensor node (b). Inset in (a): details of the horizontally grown ZnO NWs.

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

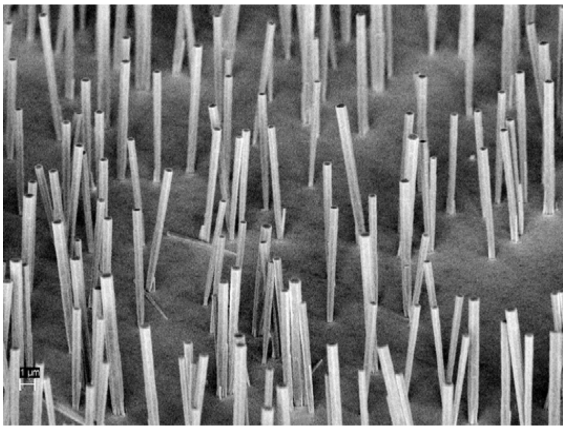

Fig. 2. SEM image of ZnO NWs grown for 24 h at 80 °C with a reactive concentration of 5 mM over a silicon substrate coated with a Cr–Au layer.

temperature control the ZnO NW morphology and aspect ratio. Fig. 2 shows a sample with NWs grown on a piece of a silicon wafer coated by two layers of Ti and Au with thicknesses of 20 nm and 50 nm respectively. It was used the hydrothermal method with a reactive concentration of 5 mM and a temperature of 80 °C for 24 h.

Using the same process, laterally aligned NWs can be grown by utilizing different materials to activate or inhibit the growth along different directions [15,19]. Two materials are used in that case: Au or ZnO seeds for the growth, and Cr layer for preventing the local growth. Any substrates such as inorganic, organic, single crystal, polycrystalline, or amorphous substrates can be used for the lateral growth of ZnO NWs, The first step was to fabricate a ZnO strip pattern covered with Cr at the top over a support silicon wafer.

After a typical wafer cleaning, a photoresist was spin coated on the substrate to get a uniform layer and subsequently patterned by optical lithography. ZnO strips with Cr on top were achieved after lifting-off with acetone. Finally, the substrate was introduced floating upside down on the solution surface for 12 h at 80 °C. It is shown in Fig. 3 that ZnO NW arrays grew from the lateral sides of the pattern with a good alignment. Moreover, more than 70% NWs were parallel to the substrate. For these reaction parameters, ZnO NWs have a diameter less than 200 nm and a length of about 4 μm. By increasing the growth time and renewing the growth solution, ZnO NWs longer than 13 μm and a diameter of ∼300 nm can be synthesized. The hexagonal cross section of NWs implies that *c* axis of ZnO NW is along its length direction. From this experience, it is clear that a selective horizontally-aligned NW arrays can be growth from the ZnO or gold stripe sidewall.

In our case, we propose the use of a thick layer of gold as seed block as well as a composite layer with several sheets of gold and chromium in order to reduce the fabrication cost. In addition, a layer of ZnO over an intermediate gold layer can be used as seed for the NW growth. Using a gold layer is a requirement dictated by the necessity of creating a Schottky barrier at this end of the NWs. The other electrode, the zigzag-shaped mass, has to be made of chromium in order to get an Ohmic contact.

Due to the semiconductor nature of the ZnO, when a metal is put in contact with ZnO, the metal–semiconductor interface created can behave as a rectifier or a resistor.

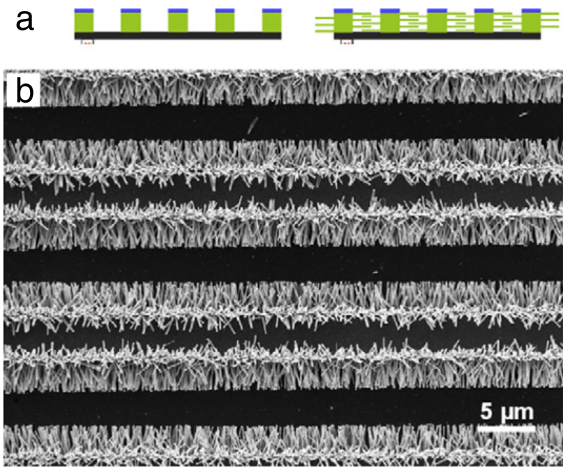

Fig. 3. (a) Schematic steps for growing patterned and laterally aligned ZnO NW arrays. (b) SEM image of ZnO NW arrays grown laterally on Si substrate.
Source: From [15].

Depending on the metal work function and the electron affinity of the ZnO, the junction will form an Ohmic or resistive contact instead of a Schottky or rectifier contact. In spite of the fact that high-quality Schottky contacts are critical for ZnO device applications, the chemical reactions between the metal and the semiconductor, the surface states, the contaminants, the defects in the surface layer, and the diffusion of the metal into the semiconductor are well-known problems in the formation of Schottky contacts.

3.2. Proposed fabrication process

The proposed fabrication process (Fig. 4) starts with a silicon wafer that only has the function of supporting the metal layer covering it. The first step is the deposition by PECVD of a thick layer of silicon oxide (i.e. 5.65 μm for 100 min at a deposition rate of 56 nm/min) that will play the role of sacrificial layer. Then, in order to perform a lift-off technique, a negative resist (Futurrex NR5-8000) is spin coated at 3500 rpm for 40 s with an acceleration of 1000 rpm/s (step #2). This resist is a negative tone photoresist designed for thick film applications and with UV exposure tools emitting at the 365 nm wavelength. The patterning procedure consist of the following steps: (1) a soft-bake of 60 s at 150 °C, (2) an UV exposure through the resonator mask (step #3), using the Karl Suss MA-6 Mask Aligner during two consecutive exposure of 10 s for a light intensity of 9 mW/s (i.e. ∼21 mJ/cm^2 for 1 μm and a light source of 365 nm), (3) a post-bake for 60 s in a hot-plate at 100 °C, (4) a development in RD6 for 20 s following for a rinsing with DI water and a carefully dry with nitrogen gas.

Afterward, a thick chromium layer is deposited by evaporation (step #5). Then, through an ultrasonic bath in acetone (step #6), the rest of metal can be lifted and removed from the wafer, obtaining the set formed by inertial mass, suspensions and anchors. A similar lift-off process is carried out for the case of the gold electrodes (Note that after the step #7, the cross section line has been moved in the figure to observe the suspensions profile). It is divided into resist spin coating (step #8), patterning

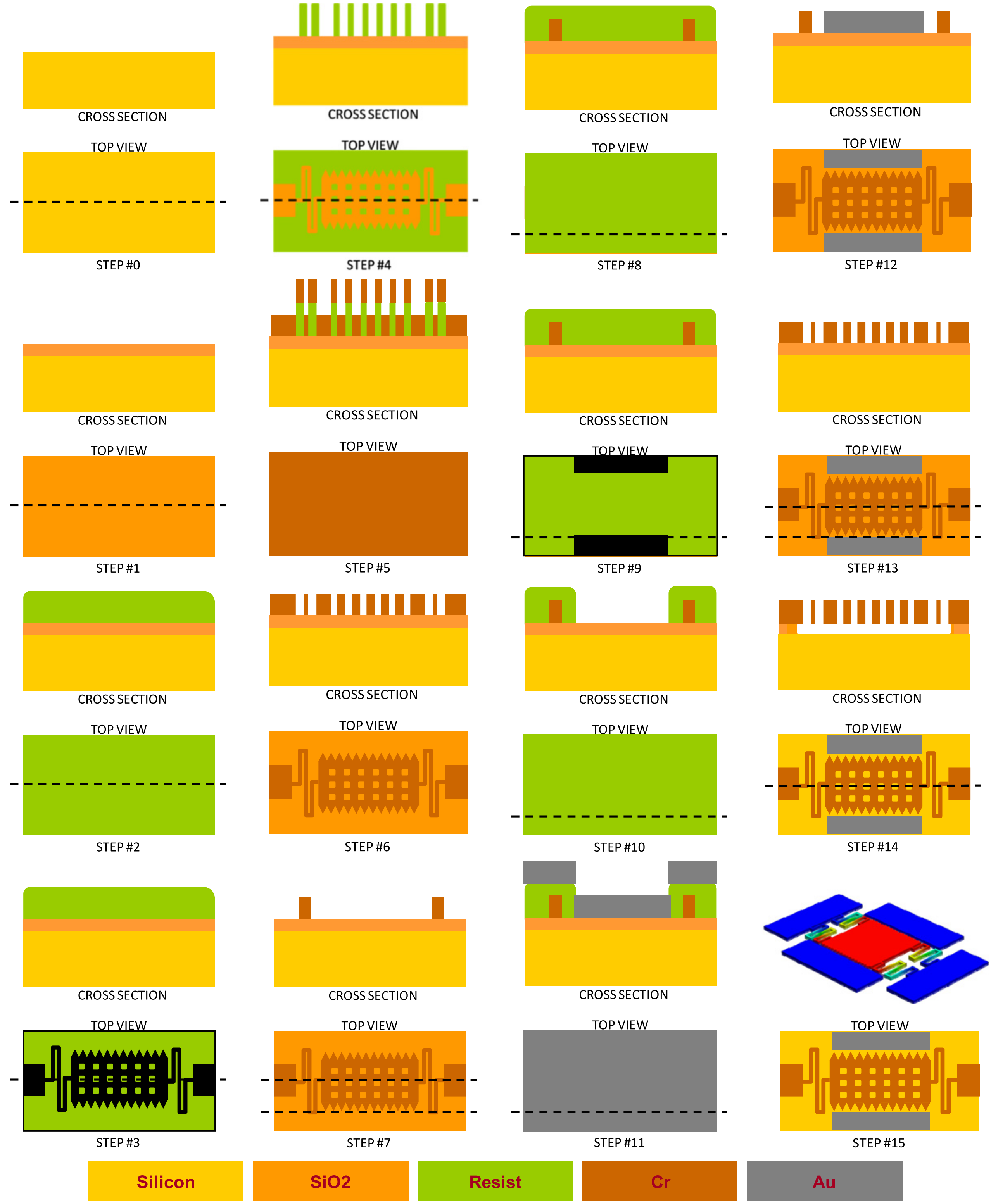

Fig. 4. Proposed fabrication process and color legend of materials. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

with gold electrode mask (steps #9 and #10), deposition of a thick layer (~4 μm) of gold or a gold composite layer (step #11) and remove of the spare metal (step #12). It is important to cover the gold surface with a chromium layer in order to avoid vertical NW growth. In that moment both electrodes for each resonator are created and the NWs can be grown by the hydrothermal method that was described above. When the horizontal NWs have the enough length to reach the corresponding zigzag electrodes, the movable structures can be released. A buffered HF (BHF) solution is used to remove the silicon dioxide placed under the movable mass (step #14). Previously, it is important to cover the whole wafer surface, except the inertial mass holes (it can be used the same mask to perform it), with

Table 1
Theoretical values of the resonance frequency (in kHz) at the first in-plane mode for every resonator. The columns show the width, length and stiffness of every single serpentine suspension. The rows show the width, length and mass value of the inertial mass.

	Mass width (μm)		100	200	300	100	200	300
	Mass length (μm)		50	50	50	100	100	100
	Mass value (μg)		0.125	0.247	0.370	0.237	0.467	0.697
25	30	177.556	379.21	269.70	220.63	275.78	196.35	160.69
50	30	97.548	281.07	199.90	163.54	204.41	145.54	119.11
100	30	67.456	233.73	166.23	135.99	169.98	121.02	99.05
150	30	51.586	204.40	145.37	118.92	148.65	105.83	86.61
25	50	32.223	161.55	114.89	93.99	117.48	83.65	68.46
50	50	17.339	118.50	84.28	68.95	86.18	61.36	50.22
100	50	11.878	98.08	69.75	57.07	71.33	50.78	41.56
150	50	9.035	85.54	60.84	49.77	62.21	44.29	36.25
25	70	5.237	65.13	46.32	37.89	47.36	33.72	27.60
50	70	2.752	47.21	33.58	27.47	34.34	24.45	20.01
100	70	1.868	38.89	27.66	22.63	28.28	20.14	16.48
150	70	1.414	33.83	24.06	19.69	24.61	17.52	14.34
25	90	1.727	37.40	26.60	21.76	27.20	19.37	15.85
50	90	0.897	26.95	19.16	15.68	19.60	13.95	11.42
100	90	0.606	22.15	15.75	12.89	16.11	11.47	9.38
150	90	0.457	19.24	13.69	11.20	13.99	9.96	8.15
Suspension width (μm)	Suspension length (μm)	Stiffness (N/m)						

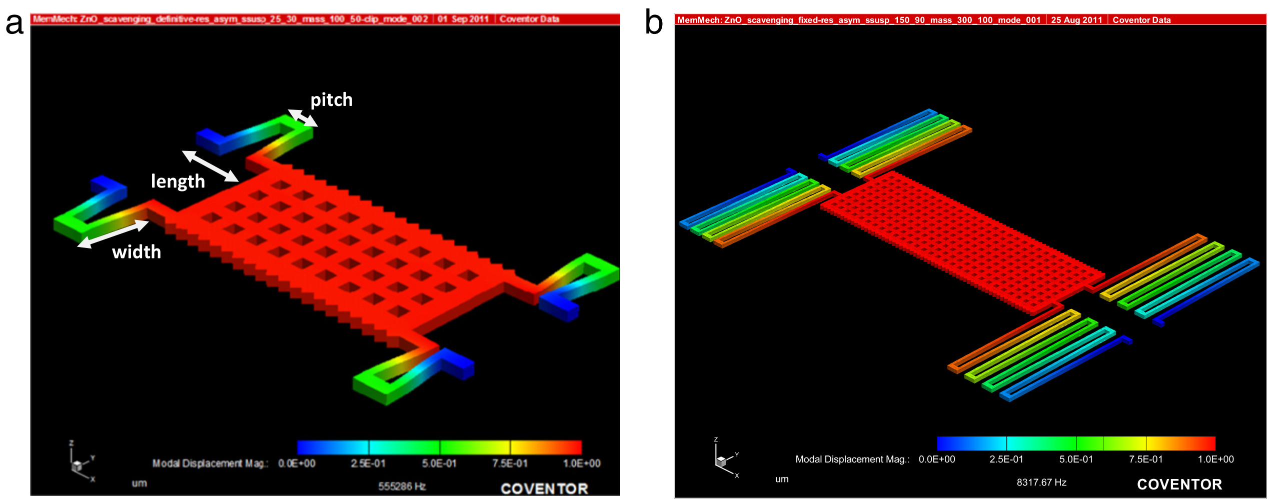

Fig. 5. FEM simulation of first in-plane resonant modes for the smallest (a) and largest (b) designed resonator with a resonance frequency of 555 kHz and 8.32 kHz respectively.

resist in order to avoid the completely etch of the ZnO NWs. A critical point drying is necessary to keep away from the sticking of the movable mass to the wafer surface due to the adhesion forces found during a normal drying.

4. Mechanical simulation and electrical estimation of the proposed energy scavenger

The layout of a 100 mm wafer with 120 chips has been carried out. It includes 12 different chip layouts that include a total of 96 resonator designs described in Table 1. The spring constant of a serpentine suspension can be found using the following expression [9]:

$$k_{serpentine} = \frac{12EI[n(a+b)-b]}{b^2(n-1)[(3a^2+4ab+b^2)n+3a^2-b^2]} \quad (1)$$

where $E = 140$ GPa is the Young's modulus of chromium, a is the pitch between two adjacent beams of the suspension (10 μm), n is the number of meanders of the suspension that can be calculated as the length of the suspension divided by the pitch and b is the width of the suspension (see Fig. 5(a) for more details)

Finally, I is the moment of inertia that can be calculated as,

$$I = \frac{t w_s^3}{12} \quad (2)$$

where t is the thickness of the resonator, and w_s is the width of the suspension's beams.

Every resonator consists of four serpentine-type suspensions that hold the zigzag-shaped inertial mass. The inertial mass surface presents holes to allow the release of the structure by wet etching of the sacrificial oxide layer. The values of the inertial masses, $m_{inertial}$, have been extracted from FEM simulations using COVENTOR® software. With the value of the spring constant of every suspension and multiplying this value by four, we can find the effective spring constant, k_{total}, of the four suspensions that hold every resonator. Then, the resonance frequency of the first in-plane modes for every device can be estimated as:

$$f_{res} = \frac{1}{2\pi}\sqrt{\frac{k_{total}}{m_{inertial}}}. \quad (3)$$

On the other hand, from additional FEM modal simulations, we found that the resonance frequencies go from 555 kHz to 8.32 kHz corresponding to the smallest and largest resonators respectively (Fig. 5). This range approximately agrees with the theoretical values calculated and shown in Table 1.

In comparison to the commented previous works, this approach achieves several improvements: (i) it is not required an expensive AFM tip to bend the NWs, a zigzag-shaped electrode is used instead. (ii) Due to the use of ultrasonic waves and vibrations in the sound's frequency range, a resonant system is utilized to enhance the relative motion between NWs and zigzag-shaped electrode. This enhancement value is equal to the quality factor of the resonator and it means an amplification of the NW bending and consequently a generated power improvement with respect to the static electrode approach. Therefore this approach meets the advantages of both prototypes, the high voltage output of the single NW generator driven by the AFM tip and the stable and increased generated current of the original zigzag-shaped generator, together with the virtually universal availability of the mechanical excitation (ambient vibrations and sonic or ultrasonic waves).

From the Ref. [17], we can suppose that the density of the laterally-grown NWs will be ∼10 NW/ μm^2 in the sidewall of the gold electrode. The available area for NW growth is 300 μm of length (for the largest device) multiplied by 4 μm (thickness of the chromium layer). Therefore, a total of 24,000 NWs can be achieved in a single device. If every NW takes an active part in the charge generation, and from the value of 0.1 pW/NW that is obtained when a NW is bent by an AFM tip [16], we can estimate a generated power of ∼1.2 nW at resonance.

5. Conclusions

We propose a novel concept for energy scavenging from vibrations utilizing the hybridization of conventional resonant devices with ZnO NWs. A wafer layout has been designed and the fabrication process has been defined and explored. A huge variety of designs have been included, thus a wide frequency range can be studied. This approach can be used to power wireless sensor nodes at the micro and nanoscale level. In addition, this generator could be integrated with other elements that can be achieved 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. FEM simulations also show the feasibility of fabricating this kind of devices to scavenge energy from vibrations in the sonic to ultrasonic frequency range.

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Zhong Lin (ZL) Wang is the Hightower Chair in Materials Science and Engineering, Regents' Professor, Engineering Distinguished Professor and Director, Center for Nanostructure Characterization, at Georgia Tech. Dr. Wang is a foreign member of the Chinese Academy of Sciences, fellow of American Physical Society, fellow of AAAS, fellow of Microscopy Society of America and fellow of Materials Research Society. Dr. Wang has made original and innovative contributions to the synthesis, discovery, characterization and understanding of fundamental physical properties of oxide nanobelts and nanowires, as well as applications of nanowires in energy sciences, electronics, optoelectronics and biological science. His discovery and breakthroughs in developing nanogenerators establish the principle and technological road map for harvesting mechanical energy from environment and biological systems for powering a personal electronics. His research on self-powered nanosystems has inspired the worldwide effort in academia and industry for studying energy for micro-nano-systems, which is now a distinct disciplinary in energy research and future sensor networks. He coined and pioneered the field of piezotronics and piezo-phototronics by introducing piezoelectric potential gated charge transport process in fabricating new electronic and optoelectronic devices. This breakthrough by redesign CMOS transistor has important applications in smart MEMS/NEMS, nanorobotics, human-electronics interface and sensors. Dr. Wang's publications have been cited for over 43,000 times. The H-index of his citations is 101. Details can be found at: http://www.nanoscience.gatech.edu