Design, Fabrication and Characterization of a vibrational-driven piezoelectric microgenerator

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Abstract. The research conducted during this thesis involves the “*Design, Fabrication and Characterization of a Vibrational Piezoelectric Microgenerator*”, with use in wireless sensor networks, to make them autonomous. At the beginning, there is a review on some the latest cantileverd-based MEMS piezoelectric microgenerators and their characteristics. Also, there is a small review on the field of Piezotronics and its applications. The prototype microgenerator developed and presented in this thesis is a combination of MEMS technology and nanostructures of the piezoelectric material ZnO, able to convert low vibrations (~100Hz) into electricity. After, there is an extensive review on the basic equations that have been taken into account for the optimization of the design and fabrication processes. Arrays of vertical nanowires as well as uniform nanotextured films of ZnO were fabricated, simulated and characterized, taking into account the influence of each parameter. The MEMS microgenerators were successfully fabricated, packaged and characterized to achieve optimum results. Finally, an alternative approach on the fabrication of flexible nanogenerators is presented. Nanogenerators with either Au or Al electrodes were fabricated on flexible substrates, providing power outputs up to 30nWatts on an external load of 2MΩ.

Keywords: Energy Harvesting, MEMS, ZnO nanorods, Hydrothermal Method, Microgenerators, Flexible Nanogenerators

1 Introduction

The recent developments in the field of wireless sensor networks has attracted much interest, enabling them for further applications such as temperature or pressure monitoring, detection of toxic chemicals or gases or positioning of people in commercial buildings. Developments also in the field of VLSI have resulted in low power sensor

*Dissertation Advisors: [1]Aggeliki Arapoyianni, Professor – [1]Dimitrios Syvridis, Professor – [2]Dr. Christos Tsamis, Researcher nodes (~1mW). Continuous powering these nodes is critical because it directly affects their lifetime and proper function, making the common way of powering (batteries) quite undesirable. Also, the total volume of the sensor node is affected by the size of the battery. Therefore, there is a need to develop new and exciting technologies that provide the node with the ability to harvest energy from the environment, making it self-sustainable. In this thesis, we explored the energy harvested from mechanical vibrations in order to fabricate microgenerators, utilizing MEMS processes and piezoelectric nanostructures.

2 Related Work

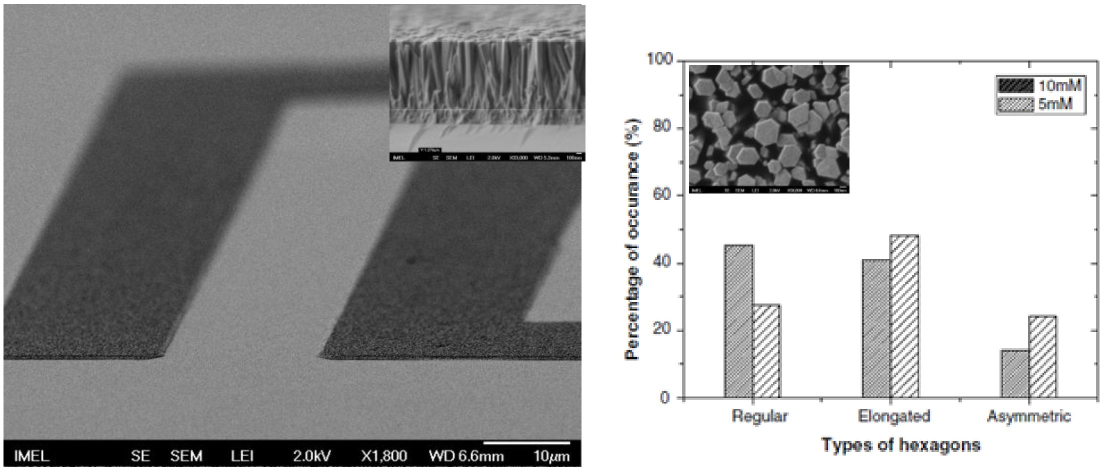
In the past few years there have been a number of publications regarding the fabrication of MEMS piezoelectric microgenerators reporting interesting results. MEMS microgenerators consist of a cantilever beam, usually with an end proof mass, metal electrodes and piezoelectric films. A large number of the known MEMS microgenerators, however, use PZT [1-4], which even though it produces great voltages due to mechanical deformations, it is toxic and therefore, they can be no biological or environmental applications.

ZnO was chosen as the piezoelectric material in this thesis, mainly due to its ability to form in various nanostructures and the fact that it has no toxicity and poses no threat to either the environment or organisms. The originality of this work rests on the combination of MEMS processes and ZnO nanostructures to develop microgenerators to power low-consumption electronics.

3 ZnO Nanostructures

3.1 ZnO nanorods

There are a number of known techniques used to produce plain and complex ZnO nanostructures, however our own results were based on the hydrothermal method. ZnO nanorods have beed fabricated on various substrates, taking into account all the necessary parameters involved (temperature, pH, precursor’s concentration, time of growth) and the effects each one them has when they change. Patterned growth of vertical ZnO nanorods has been achieved and a thorough statistical analysis has been performed to study the morphological characteristics of the resulting structures (Fig. 1a-b). The inset in Figure 1a shows the verticality, while the one in 1b the different ZnO nanorods we fabricated [5].



(a) (b
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Figure 1: (a) Patterned growth of vertically aligned ZnO nanorods. The inset shows the verticality of the nanorods, (b) Statistical analysis of the morphology of the resulting structures. The inset shows the different types of the resulting hexagons.

Based on the theory of chapter 2, simulations of our ZnO nanorods have been performed, in order to calculate the piezoelectric potential drop when there were subjected on known mechanical deformations. An extensive and novel work was carried away, taking into account not only the morphological results above but also several electrodes' configurations, in order to achieve the maximum theoretical power output for a given area of growth. The results were well within the range of the already published values [6].

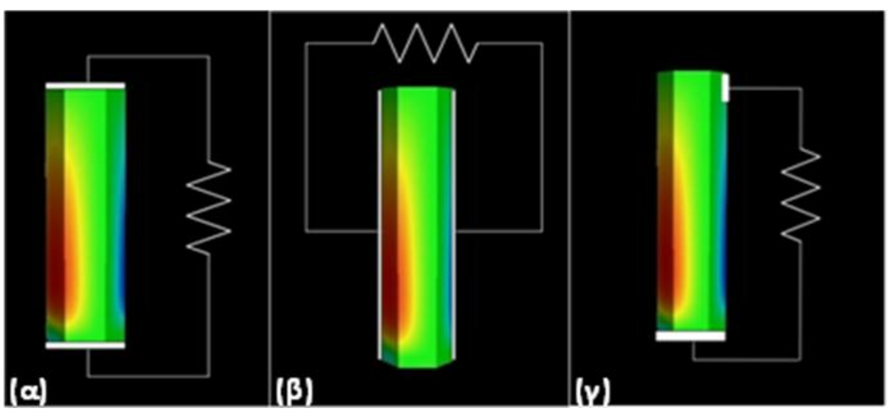
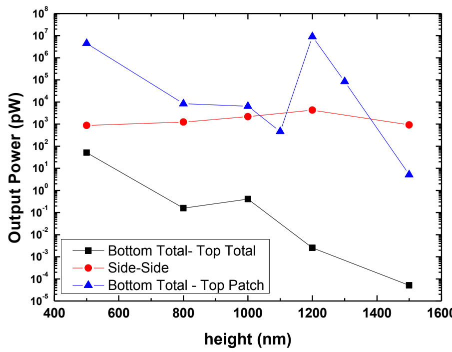
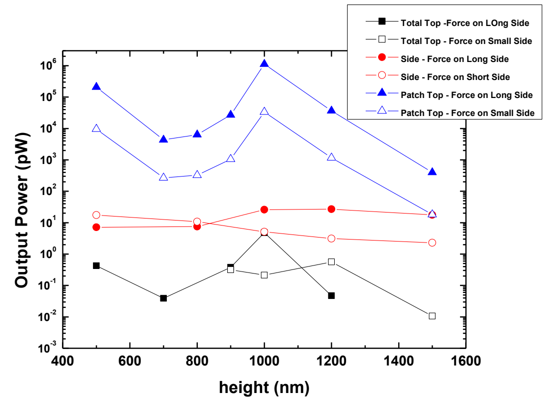


Figure 2: Three different topologies for the electrodes on the ZnO nanowire



Graph 1: Simulated power output for regular hexagons with a diameter of 100nm.



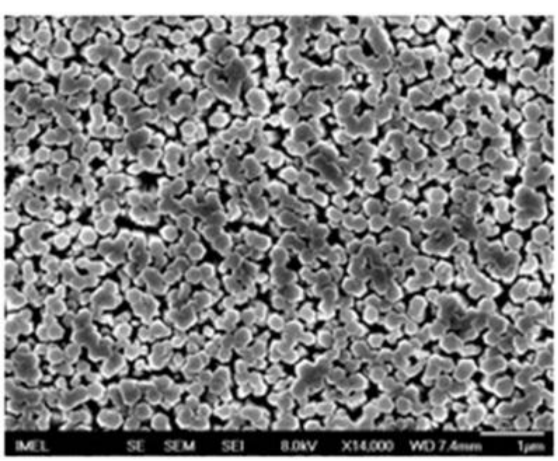
Graph 2: Simulated power output for elongated hexagons with a diameter of 300nm and the force at both the long and the small side

Table 1: Summary of the simulated power outputs based on the morphology of the nanorods and compared to known published values

Electrode Topology	Power (low aspect ratio NRs)	Power (high aspect ratio NRs)	Power measured from regular hexagonal NWs
Total Bottom – Total Top	33.44 μW/cm^2	0.47 mW/cm^2	1 mW/cm^2 (Wang et al. 2006)
Total Bottom – Top Patch	0.13 pW/cm^2	**2.47 mW/cm^2**	

3.2 ZnO nanotextured film

Further exploiting the hydrothermal method we successfully fabricated a uniform nanotextured ZnO film consisting of vertically aligned ZnO nanorods fused together. The purpose was to use this easy, low-cost method to fabricated uniform columnar films for use as active material in our microgenerators [7].



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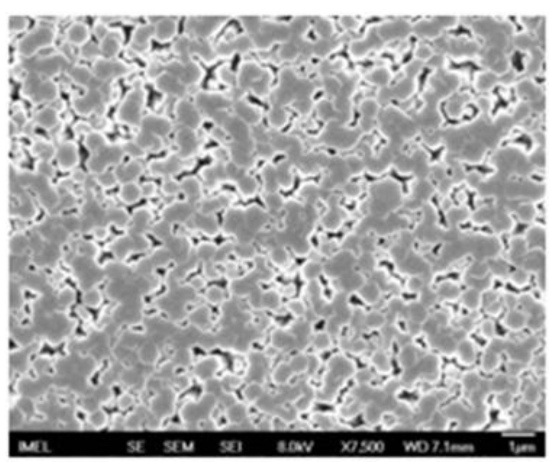

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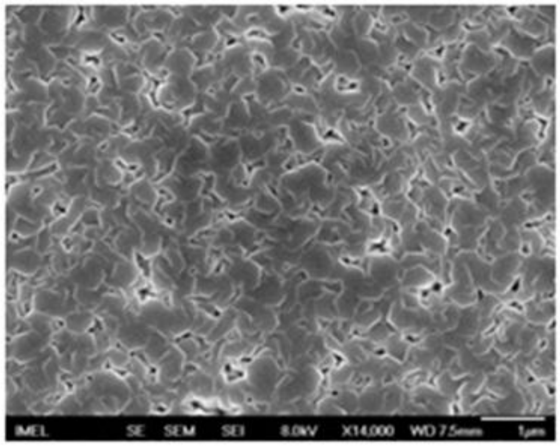

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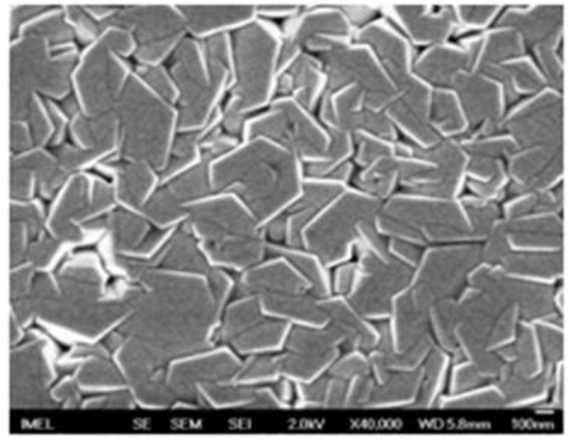

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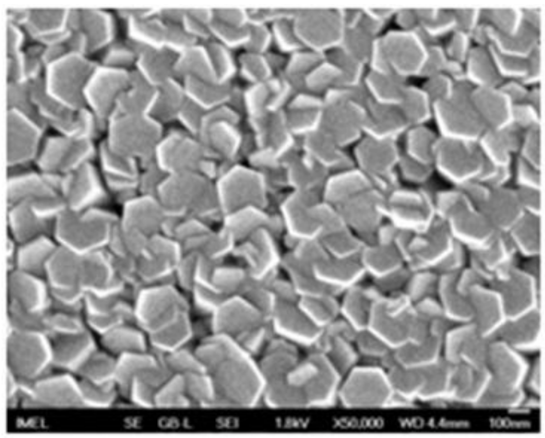
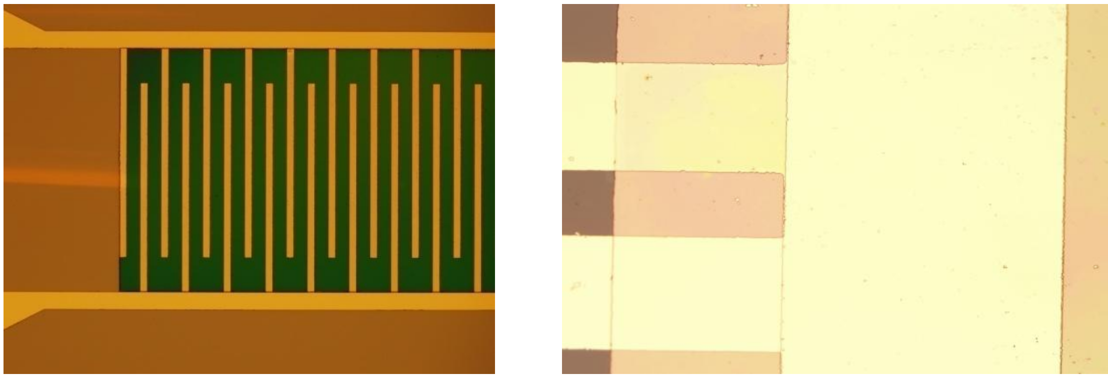


(e)

Figure 3: Fabrication of ZnO nanotextured films for concentrations of (a) 100mM, (b) 200mM, (c) 400mM, (d) 500mM, (e) 1000mM.

3.3 Characterization of ZnO nanotextured films

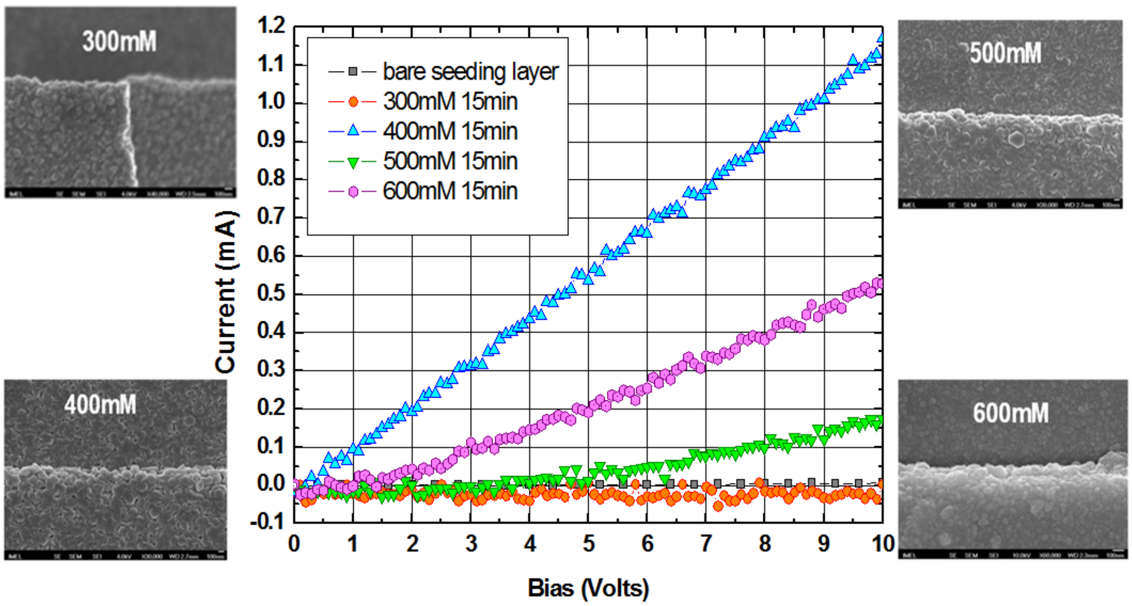
Further investigation in the fabrication of ZnO nanotextured films was carried away, in order to identify the optimum parameters and therefore produce the film with the best morphological and electrical characteristics. To that end, the nanotextured film was fabricated on two sets of electrodes: (a) Interdigitated and (b) bottom-top. I-V characteristics were performed in order to investigate the contact between the metal and the ZnO.



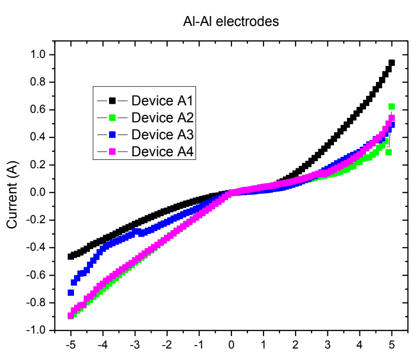
(b)

(a)

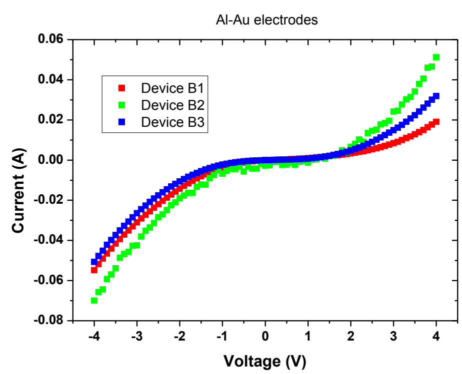
Figure 4: (a) Intedigitated electrodes, (b) Top-Bottom electrodes.



Graph 3: I-V characteristics on the IDE electrodes, based on the morphology of the resulting nanotextured film (inset SEM pictures).



Graph 4: I-V characteristics using bottom and top Al electrodes.



Graph 5: I-V characteristics using bottom Al electrode and top Au electrode.

Results indicated that the metal-ZnO contact, when using Al as electrode, is not Ohmic as expected but shows signs of Schottky diode. The microgenerator's principle of operating is based on the Shottky diode between the ZnO and the metal, so the preliminary results indicated that Aluminum can be used for making the electrodes in the microgenerator, making the full process CMOS compatible [8].

4 Fabrication – Characterization of MEMS microgenerators

We have successfully fabricated uniform columnar ZnO nanotextured films on metal substrates, as they will provide the electrodes for the generator. The proposed MEMS microgenerator is illustrated on Figure 5. It consists of a cantilever beam made of Si, with top-bottom metal electrodes, a piezoelectric film in between and an end proof mass. The dimensions of the cantilever and proof mass were specifically designed so the whole system resonates at low vibrations ~100Hz.

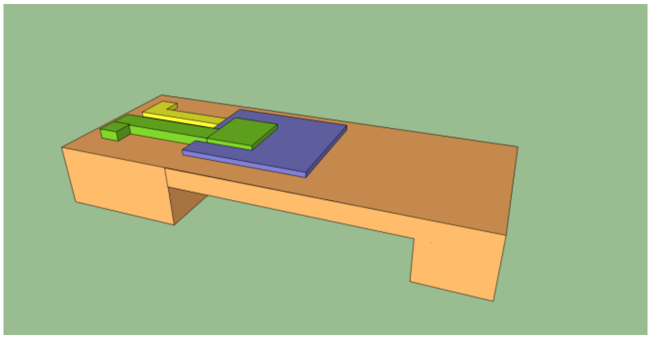
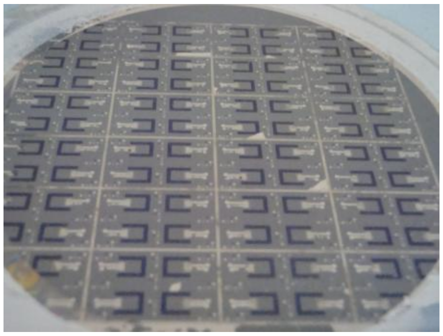
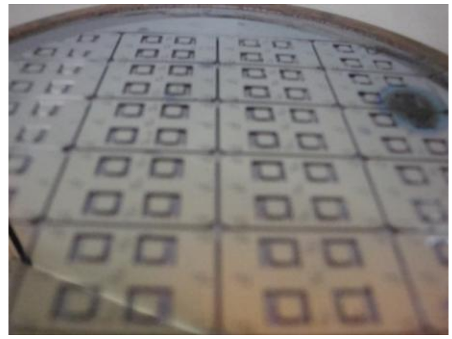


Figure 5: Illustrated schematic of the cantilever-based MEMS microgenerator

The novelty of our microgenerator lies in both the use of SOI technology and the ZnO nanotextured film. SOI wafers was preferred than standard Si ones, in order to simplify the process and make use of the buried oxide as an etch-stop during the etching for the release of the cantilever. The masks for the lithography were designed in AutoCAD and fabricated on Aluminum-coated glasses. Figure 6 shows the front and back side of an SOI half-etched wafer, where approximately 80 devices were fabricated.



(a)



(b)

Figure 6: (a) Front and (b) back side of SOI wafer with cantilever-based piezoelectric microgenerators.

A custom-made experimental setup was used to excite externally the fabricated microgenerators, using mechanical vibrations induced by 2 speakers. Using a frequency generator it was possible to control the vibrations and also measure the corresponding acceleration. Each die from the wafer included 4 separate microgenerators (for future parallel or series connection) and was wire-bonded on custom-made PCBs. The output signal was recorded in real-time using a digital oscilloscope. Figure 6 shows the experimental setup and a close look of the die.

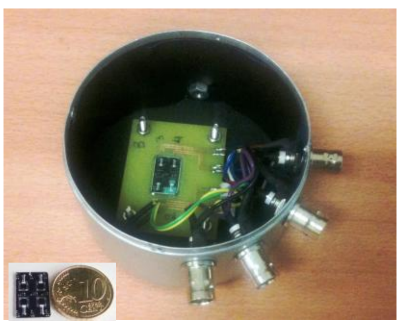


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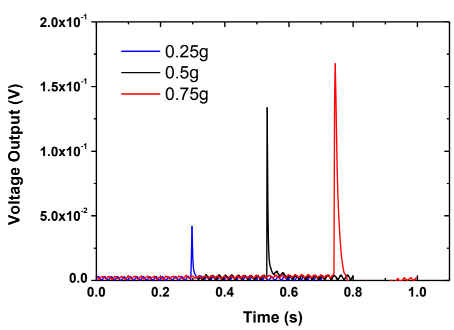
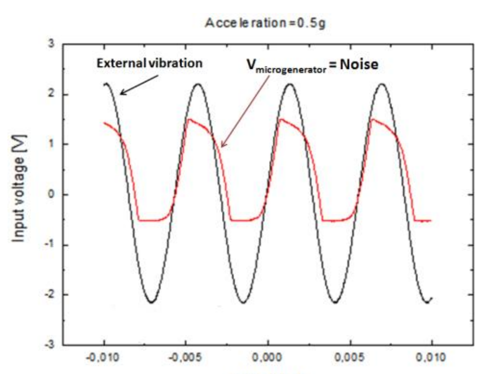
Figure 7: (a) Wire-bonded die on PCB. Inset shows the size of the die. Inset shows the actual size of the die consisting of 4 microgenerators, (b) Experimental setup for piezoelectric characterization.



Graph 6: Voltage spikes of the MEMS microgenerators in different accelerations.

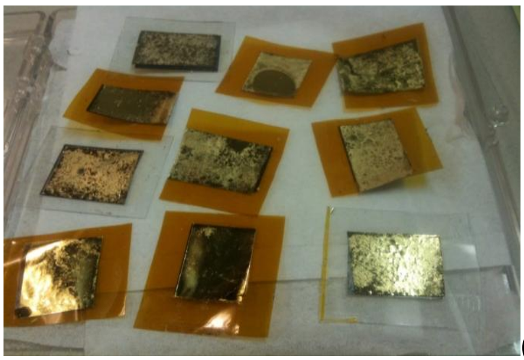


Graph 7: Voltage ouput in sinusoid excitation signal. The signal of the microgenerator is embedded in background noise.

Operation of the microgenerators was visible when the excitation was done with short strikes (spikes on Graph 6), but in the use of sinusoid signal there was only noise (Graph 7). Still, the proof-of-concept was proven. Further investigation of the properties of the ZnO nanotextured film was required, so we proceeded with the fabrication of flexible nanogenerators to study these parameters more thoroughly.

5 Flexible Nanogenerators

Through the hydrothermal method we were able to successfully fabricate nanogenerators on kapton and PET substrates with various architectures. This work was done in collaboration with Dr. Zhong Lin Wang from Georgia Tech [9]. The ZnO nanotextured film was used as the active material, while Au, Al and Pt were used as metal electrodes.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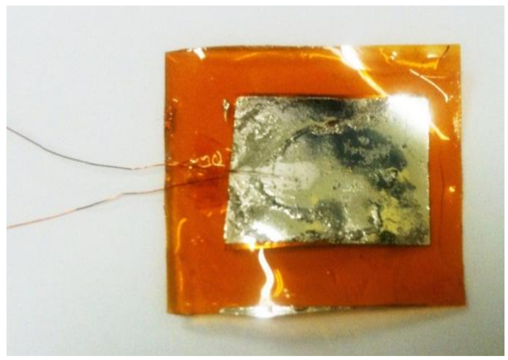
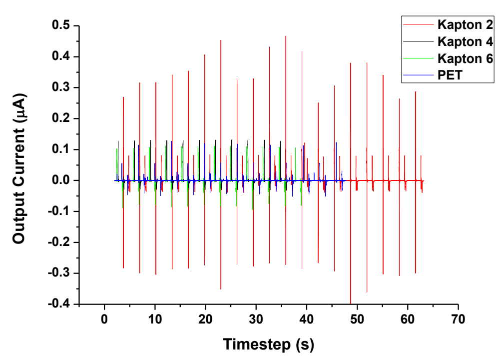

(b)

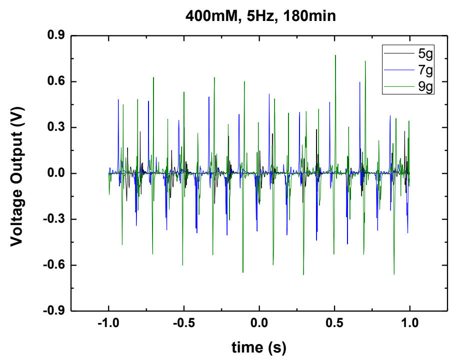
Figure 8: Flexible nanogenerators with (a) Au electrodes and (b) Al electrodes.

The characterization of these devices was performed using a techno-pneumatic piston to bend the nanogenerator, while the output signal was measured in real-time with a digital oscilloscope. The output voltage reached in several cases V_{p-p}=4 Volts with I_{p-p}= 800nA for controlled vibrations. Characterization of the devices occurred both in the labs of Georgia Tech and Institute of Microelectronics, providing interesting results.

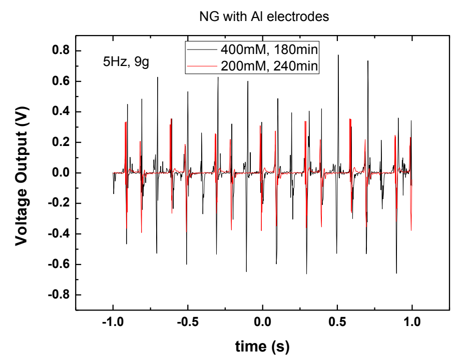
Figure 9: Experimental setup in Georgia Tech.



Graph 8: Current output measured .

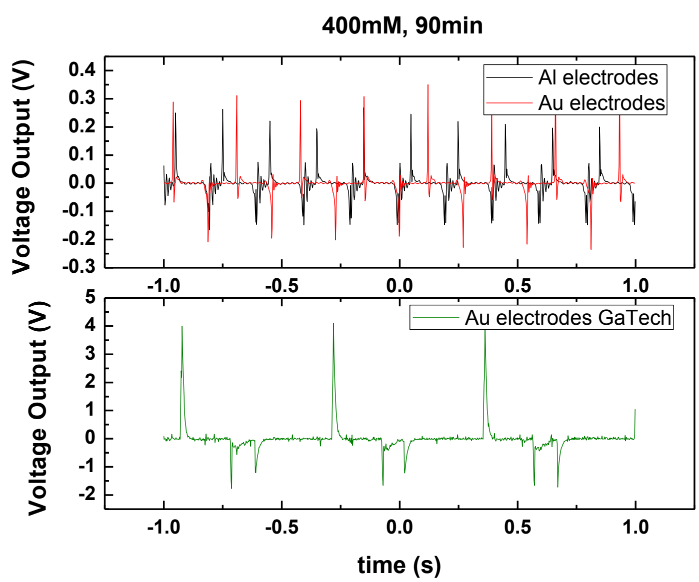


Graph 9: Voltage ouput vs acceleration for nanogenerators with Al electrodes.



Graph 10: Voltage output vs solution concentration for given acceleration and film thickness.

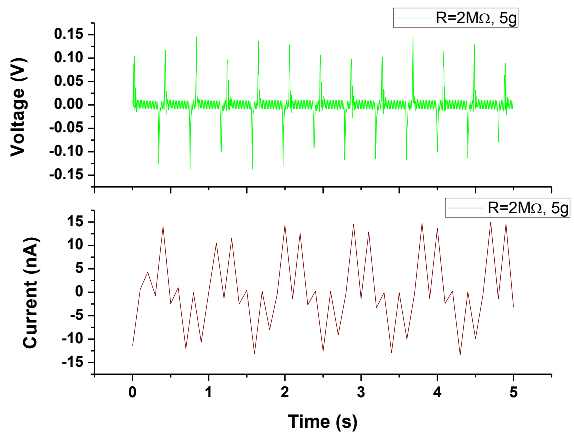
As indicated in Graphs 9 and 10, the voltage output is directly proportional to the acceleration and the morphological characteristics of the nanotextured film. Optimum concentration was 400mM with a growth time of 180min, resulting in film thickness of ~2μm. In order to have a direct comparison between the two different experimental setups, the nanogenerators with the Au electrodes were also measured in our lab giving the results presented in Graph 11.



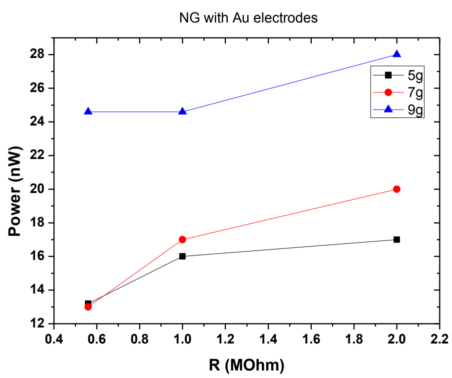
Graph 11: (Top) Voltage output of the nanogenerators with Al electrodes and Au electrodes measured in our lab, (Bottow) Voltage output of the Au nanogenerators measured in Georgia Tech.

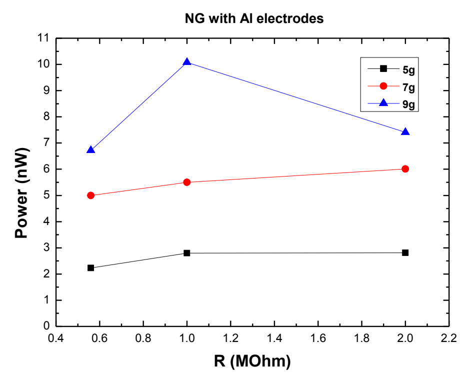
Graph 11 shows the comparison between the 2 experimental setups, where it is quite obvious that the voltage output is also depending on the manner in which the flexible substrate is bent. Higher voltages were measured in GaTech which gives room for further investigation and optimization of our own technique.

The next step was to simultaneously measure the voltage and current, using different resistive loads, in order to calculate the power output of such nanogenerators. Graph 12 shows a sample of these measurements, while in Graphs 13 and 14 the power is presented.



Graph 12: Voltage and Current ouput of an Al nanogenerator over a R_L=2MΩ for given acceleration.





Graph 13: Power vs Resistive load for different accelerations for an Au nanogenerator.

Graph 14: Power vs Resistive load for different accelerations for an Al nanogenerator.

The power ouput is directly proportional to the acceleration, as expected and we also observed an increase when using Au electrodes. However, the power generated from the Al electrodes is in the same range, which suggests that use of Aluminum as electrode is a safe and very promising choice [10].

6 Conclusions

We have presented an easy, low-cost, large-scale method for fabricating high-aspect ratio ZnO nanorods, as well as nanotextured films with high uniformity and promising electrical characteristics. For the first time, there has been fabrication of MEMS microgenerators using the ZnO nanotextured film and the proof-of-concept was proved. Optimization of the properties of the nanotextured film occurred through the fabrication and characterization of flexible nanogenerators, generating power up to 30nWatts. Further investigation is required to optimize the electrical contacts and therefore the electric properties of the nanotextured films. The flexible approach has lead into interesting applications, such as wearable electronics or smart fibers/clothes.

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