

Project III. 1B ENERGY HARVESTING MATERIALS AND DEVICES

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Objectives:

- Design and optimization of Energy Scavengers for autonomous Microsystems
- Novel materials for high efficiency energy conversion (mechanical, thermal, etc)
- Development of single and dual-transduction mechanical harvesters for improved power characteristics
- Device fabrication and characterization

Funding:

"Development of Innovative sensor systems offering distributed intelligence – MEMSENSE", National Funds and European Regional Development Funds, NSRF 2007–2013, contract no. 45 (5/2009 - 4/2012)

Research activities and main results within 2010

Energy Scavenging from the ambient has been actively explored using several methods such as solar power, electromagnetic fields, thermal gradients, fluid flow, energy produced by the human body, and the action of gravitational fields. Most of all, mechanical vibration is a potential power source which is easily accessible through Microelectromechanical Systems (MEMS) technology for conversion to electrical energy. The reported examples use a mass–spring system which resonates when the frame of the device is vibrated. The motion of the mass relative to the frame is damped by one of several energy conversion mechanisms, namely electromagnetic force, electrostatic force, or piezoelectric force.

From these scavenger types, the ones based on electromagnetic and piezoelectric principle appear to be the most promising ones and has been the main target of our activities. Furthermore, our research effort focuses on an innovative concept and design approach, targeting to a novel energy scavenger, capable of harvesting mechanical vibration energy with the aid of two transduction mechanisms. Additionally, our research efforts are also focused on the development of novel piezoelectric materials.

ZnO nanorod arrays for efficient energy conversion

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ZnO nanostructures -owing to their multifunctional nature that combines semiconducting and piezoelectric properties- have successfully demonstrated their ability to efficiently convert nanoscale mechanical energy into electric energy, becoming thus the most prominent candidates for the development of nanogenerators. During this year, we have continued exploring the capabilities of the cost-efficient, low-temperature bottom-up method developed at the institute for the production of ZnO nanorods (NRs) on pre-patterned surfaces (Fig.1a). Analysis via FEM simulations of the expected potential across the nanorods when subjected to mechanical deformation -taking into account the nanorods' size and shape distribution (Fig1b), an inherent trait of the hydrothermal growth - has revealed that the this method not only allows for high tolerance in the control of the structural properties of the resulting nanorods, but suggests that the morphological diversity of the resulting

nanostructures can –in some cases- lead to higher conversion efficiencies compared to highly-ordered arrays.

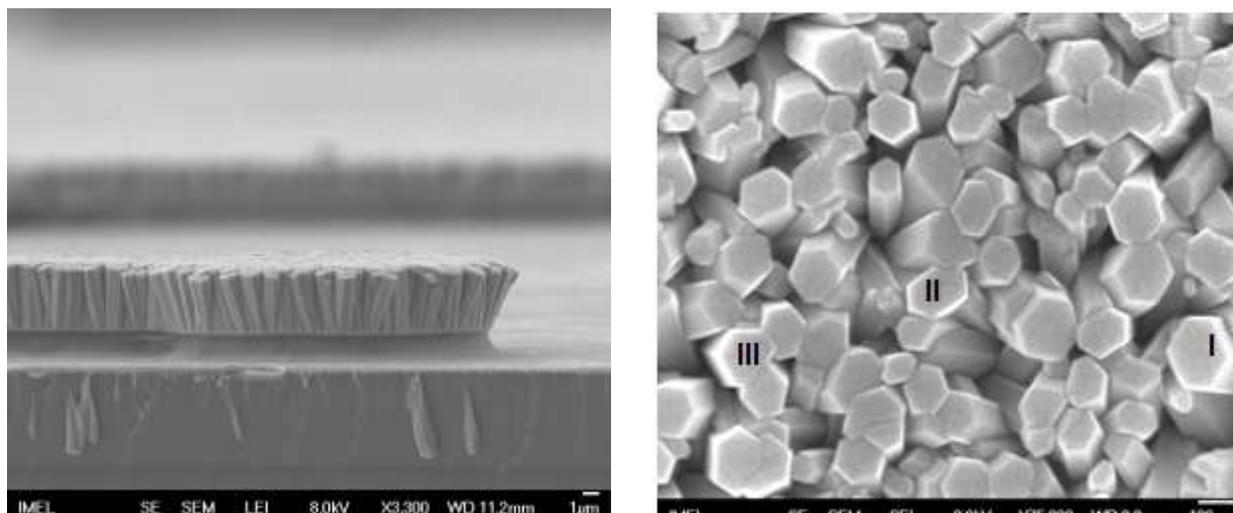


Figure 1 (a) SEM images of patterned areas at the wafer-scale where ZnO nanorods have been grown using the hydrothermal technique, (b) a close-up view of the various NR shapes that co-exist in the array: (I) purely hexagonal NRs, (II) elongated hexagons and (III) asymmetric hexagons.

For each NR shape the piezoelectric conversion efficiency was examined as a function of the geometrical characteristics and as a function of the possible electrode configuration (fig. 2). It was demonstrated that activation of additional deformational modes can be achieved when the external stimulus that deflects the nanorods is applied at certain directions, due to torsion of the elongated nanorods. Elongated NRs can produce power at the same levels as the regular hexagonal NRs (when the force is applied to the long edge), while the random orientation of the elongated electrodes (simulated as a force applied on the small side) contributes to the power generation albeit at lower levels (fig.3). In other words, the elongated NRs are still exploitable for power generation alongside the “perfect” hexagonal wurtzite NRs.

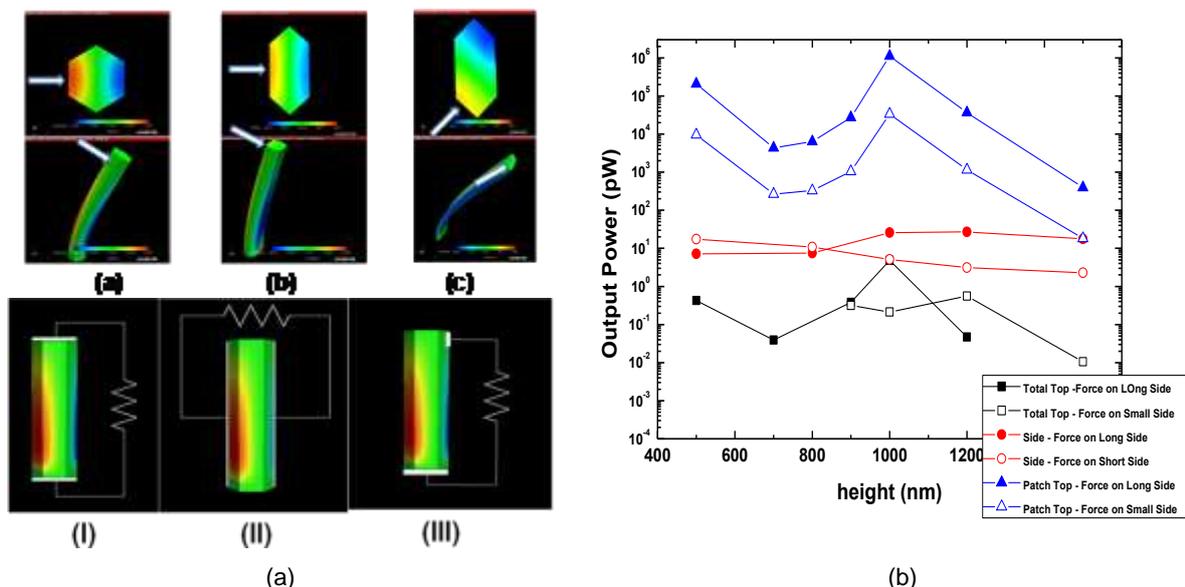


Figure 2 (a) FEM simulations for the Piezoelectric Potential for (a) regular hexagonal NRs, (b) elongated hexagonal NRs where the force is applied to the long side and, (c) and elongated hexagonal NRs where the force is applied to the short side. The three metallization configurations examined are: (I) Total Bottom– Total Top Electrode, (II) Side Electrode and (III) Total Bottom–Top Patch. (b) Output power per elongated NR for the three metallization configurations when a 100nN force is applied vertically to the long edge (solid symbols) and to the small edge (open symbols). Triangles: TB-TT ; Circle: SEs and Squares: TB-TP.

This study has indicated that the topological features of the electrodes play a key role in the possible extracted power. The easiest-to-implement configuration, namely using top and bottom electrodes (fig

2. I), is the least advantageous one since large electrodes can perturb the electrical potential distribution. On the contrary, using a metal patch as the top electrode (fig. 2 III) provides the highest output power for all types of NRs, but it is the most challenging technological approach.

In summary, it became evident that the combination of the FEM-modelling with the fine-tuning of the growth parameters of the suggested hydrothermal technique can provide a valuable methodology for the optimization of the statistical distribution of various nanorod shapes and the production cost-efficient nanowire arrays suitable for highly-efficient nanogenerators.

Growth and characterization of uniform, highly-textured ZnO films via the hydrothermal growth technique

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In addition we explored an alternative approach to fabricate ZnO films as piezoelectric materials without having to recur to high-cost deposition techniques, while circumventing the challenges posed by the formation of metallic contacts to vertically aligned nanowires. The suggested method results in highly-textured ZnO films with columnar structure that can readily be implemented into any micromechanical structure (fig. 1) providing a means for large-scale applications and a facile, inexpensive and rapid approach to piezoelectric films, up to several μm thick. This method is based on the already-known and widely-employed hydrothermal growth technique, and apart from its low cost and compatibility with standard microfabrication techniques at wafer scale, it has the additional advantages that it is conducted at low temperatures ($T < 120^\circ\text{C}$), it is non-hazardous and environmentally-friendly.

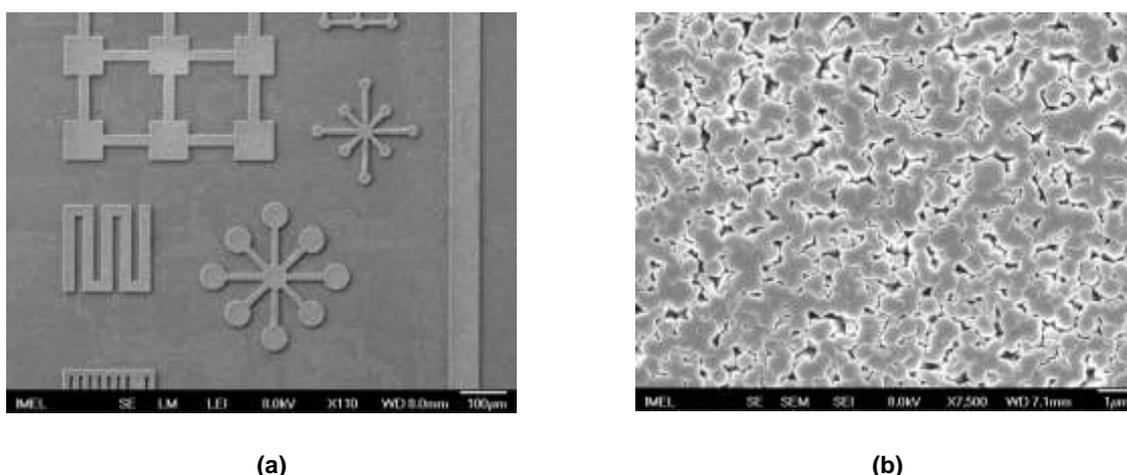


Figure 1 SEM photographs of grown nanostructured ZnO films (a) in various patterns showing the applicability of the method to any kind of structure at the wafer-scale, and (b) plan view of a hydrothermally grown film. Inset: cross-section showing that the films can be developed to several μm -thick structures.

In order to verify the applicability of the suggested method to wafer-scale and to examine its full compatibility with standard MEMS fabrication steps, ZnO nanostructured films were grown on top of interdigitated electrodes (fig. 4) as proof-of-concept devices. The I-V characteristics of the films examined through the IDE-devices are summarized in fig.4, where also the electrical behaviour of the bare seeding layer is included as reference. It can be seen that the electrical behaviour of the developed films is rather complex and cannot be related in a straightforward manner to the conditions of the hydrothermal growth.

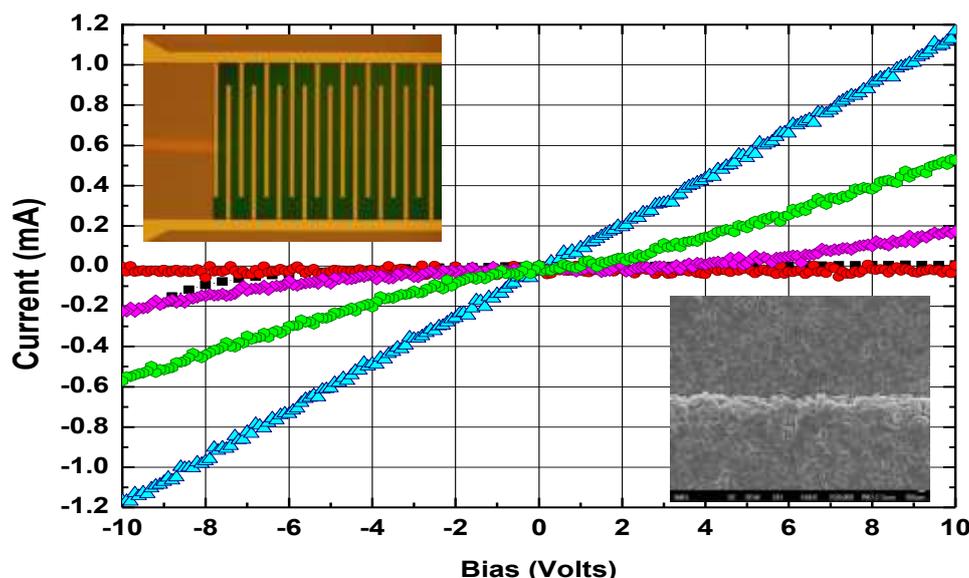


Figure 4 I-V characteristics of the hydrothermally grown films on top of the Au IDEs for 15min at 89°C compared to the bare seeding layer (black squares). Concentrations used: 300mM (circles), 400mM (triangles), 500mM (diamonds) and 600mM (hexagons). Top Inset: typical optical microscope image of Au IDEs covered with a hydrothermally grown ZnO nanostructured film. Bottom Inset: SEM image of a hydrothermally grown film on top of the IDEs

Upon close examination of the hydrothermally grown films, it became evident that the electrical characterization can be employed to provide an indirect insight on the structural quality of the films. Further investigation is though required in order to fully assess how the I-V measurements can be used for the evaluation of the hydrothermal method, since only one growth parameter (namely the concentration) was studied via the electrical measurements.

PROJECT OUTPUT IN 2010

Publications in International Journals

1. "Growth of ZnO nanorods on patterned templates for efficient, large-area energy scavengers", G. Niarchos, E. Makarona and C. Tsamis, *Journal of Microsystem Technologies*, 16, 669–675, 2010

Conference Presentations

1. "Low-cost ZnO Nanorod Arrays for Nanogenerators of Improved Conversion Efficiency", G. Niarchos, E. Makarona, C. Tsamis, Poster Presentation at the 36th International Conference on Micro and Nano Engineering 19-22 September 2010 Genoa (Italy)