Scaling Prospects in Mechanical Energy Harvesting using Piezoelectric Nanostructures

G. Ardila, R. Hinchet, M. Mouis, L. Montès
IMEP-LAHC, Joint Research Unit, CNRS / Grenoble-INP / Université Joseph Fourier / Université de Savoie
Grenoble-INP/Minatec, 3 parvis Louis Néel, Grenoble, France
ardilarg@minatec.inpg.fr

Abstract — **The combination of 3D processing technologies, low power circuits and new materials integration makes it conceivable to build autonomous integrated systems, which would harvest their energy from the environment. In this paper, we focus on mechanical energy harvesting and discuss its scaling prospects towards the use of piezoelectric nanostructures, able to be integrated in a CMOS environment. It is shown that direct scaling of present MEMS based methodologies would be beneficial for high-frequency applications only. For the range of applications which is presently foreseen, a different approach is needed, based on energy harvesting from direct real-time deformation instead of energy harvesting from vibration modes at or close to resonance. We discuss the prospects of such an approach based on simple scaling rules.**

Keywords- piezoelectricity; nanowire; mechanical energy harvesting; scaling rules

I. Introduction

The improvement of the energetic autonomy of future nano and microsystems by energy harvesting energy from the environment is a topic of growing interest in the scientific and industrial community. Energy can be harvested from sources such as incident light, heat, radiofrequency, vibrations or mechanical impacts [1]. This strategy can lengthen battery autonomy in mobile applications, which are currently one of the largest markets in telecommunications. In other applications, such as sensor networks, energetic autonomy would provide a number of advantages: it would allow energy supply wiring to be suppressed while avoiding the additional maintenance costs due to the replacement or charging of batteries. For large sensor networks, wiring would anyway be impossible due to weight, cost and reliability issues. On the other hand, battery management can be very complicated when the sensors are not easily accessible.

In this paper, we will focus on the harvesting of mechanical energy using piezoelectric materials. After having recalled the principle of energy harvesting using MEMS structures, we will discuss the consequences of device scaling down and show that a change of paradigm is necessary to harvest energy from nanostructures in the range of frequencies of interest for most present fields of applications. This has the additional advantages of extending the bandwidth, suppressing the need for high quality factors and allowing energy harvesting from random signals such as those arising from human activity.

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II. Energy harvesting using resonant MEMS

At microscale, the most widely used device architecture for mechanical energy harvesting consists in a seismic mass placed at the end of a piezoelectric beam. Beam deformation produces an electric potential difference which is converted into electrical energy. This system realizes a mechanical resonator, the design of which is optimized to increase energy transfer at a given resonance frequency. The aim is to increase the quality factor (Q) of the resonator, but at the expense of a narrower bandwidth [1].

The energy density reported for MEMS piezoelectric devices is typically in the range of 0.1 mW/cm^3 to 40 mW/cm^3 [1] at low frequency (<150Hz) and input accelerations between 1 m/s^2 and 10 m/s^2. For industrial applications, two commercial solutions are presently provided by Midé and Perpetuum. Several monitoring integrators, such as General Electrics, are using their power supply solution in wireless sensors for rotating machines. The main issues are price, volume, bandwidth and minimum input acceleration. Typical devices from Midé and Perpetuum deliver 15 V with a power density of 9 mW/cm^3, and 5 V with 20 mW/cm^3, respectively. The bandwith is rather narrow (50 Hz-150 Hz) and the minimum acceleration is about 1 m/s^2. On principle, resonant oscillators can only harvest energy in a narrow band of frequencies, while most real applications provide mechanical inputs with a wider frequency spectrum. As reviewed in [4], many techniques have been proposed to overcome this issue, such as, for instance, arrays of structures with different resonant frequencies, amplitude limiters, coupled oscillators, nonlinear springs, bi-stable structures and large inertial masses with a high degree of damping.

At MEMS scale, many piezoelectric materials have been studied: from natural crystals like quartz, compound semiconductors such as nitrides (AlN for example), oxides such as PZT ($Pb(Zr_xTi_{1-x})O_3$) and polymers such as PVDF (polyvinylidene fluoride) [1]. These materials are generally available in the form of ceramics, composites or thin polycrystalline layers. The materials with the best figure of merit are bulk ceramics, such as PZT. Unfortunately, their integration is not straightforward. Therefore, despite they do not show as good properties as ceramics yet, thin semiconducting nitride layers are widely studied in the literature because of their easier integration into MEMS [3].

III. ENERGY HARVESTING USING PIEZOELECTRIC NANOSTRUCTURES

A. *Piezolectric nanomaterials*

Presently, the piezoelectric materials which are mostly studied at nanoscale are ZnO [5], PVDF [6], GaN [7] and PZT [8], ZnO being the material of choice for most investigations. As shown in table 1, which displays reported values of the d_{33} coefficient (longitudinal, along c-axis), most of these materials have their piezoelectric properties improved at nanoscale. This is an advantage if used in sensors or energy harvesting systems.

TABLE I. PIEZOELECTRIC COEFFICIENT D_{33} IN NANOSTRUCTURED MATERIALS COMPARED TO BULK

Material	d_{33} [pm/V]		
	Theoretical (nanoscale)	***Experimental (nanoscale)***	***Experimental (bulk)***
PVDF	N/A	-38 [6]	-25
PZT	N/A	101 [8]	650
ZnO	168.2 [7]	14-26.7 [5]	9.93
GaN	65.8 [7]	12.8 [9]	1.86

B. *Scaling down of resonant devices towards nanometer scale*

For this study, we used cylindrical nanowires of length L and diameter D as model nanostructures. Their resonance frequency (f) can be evaluated from cantilever mechanics as:

$$f = \frac{D}{8\pi L^2}\sqrt{\frac{3E}{\rho}} \tag{1}$$

where E is the Young's modulus and ρ is the mass density [10]. The effect of scaling is displayed in Fig. 1. Reducing the diameter decreases the resonance frequency linearly, while reducing the length or reducing the general size (diameter and length in the same proportion) induces a sharp increase of the resonance frequency.

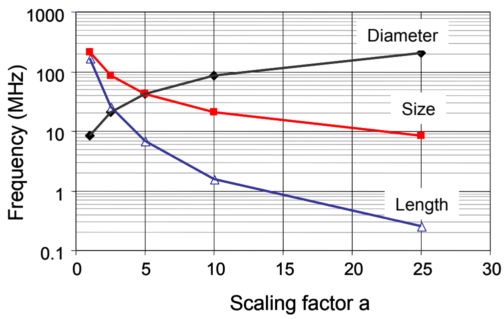

Figure 1. Effect of the reduction of size on the resonance frequency of a cantilever. The reference device (α=1) is a 50 nm wide, 1 µm long NW.

For a typical 50nm wide, 1µm long GaN nanowire (NW) (reference device, with α=1 in Fig. 1), the resonance frequency is found close to 20 MHz. In this calculation, we used recent evaluations of the Young modulus and mass density, obtained from direct measurement using an AFM probe, with values of 44 GPa and 6.15 kg/m^3 respectively [11]). Such a resonance frequency is too high for most present applications of mechanical energy harvesting, for which the range of frequencies of use is below 200Hz from human body and some structures and around a few kilohertz from machines vibrations) [1].

The energy provided by a single NW being very small (typically 10 to 20 pW for a reference ZnO NW [12]), energy harvesting systems must be based on an ensemble of NWs. It is interesting to evaluate how the resonance frequency would change in such a case. The modelled structure is depicted in Fig. 2 where vertical NWs are connected to a seismic mass. This kind of structures has been proposed in [13] and further realised, without considering any resonance effect, in [14].

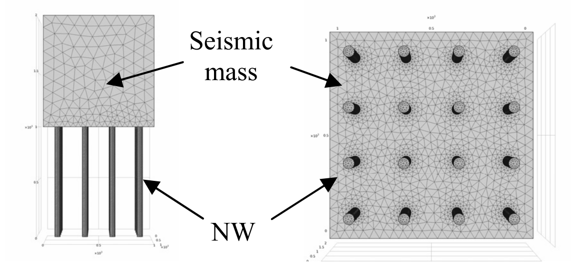

Figure 2. Side view and top view of the elementary cell simulated to calculate the resonance frequency of an array of vertical NWs connected by a seismic mass. The NWs are considered as fully clamped to a solid substrate at their bottom. The seismic mass is supposed to be made of tungsten.

Simulations based on the Finite Element Method were used to calculate the influence on the resonance frequency of such parameters as the area of the array, the density of NWs (number of NWs per unit area) and the value of the seismic mass. Calculations were performed for ZnO. It was found that the simulation of a 1 µm^2 area was sufficient to represent the response of larger devices. Our reference structure consisted of a 100 NW/µm^2 array with 1 µm long NWs and a 1 µm thick seismic mass. This density corresponds to 50 nm wide NWs spaced by 50 nm. As shown in Fig. 3, the resonance frequency can be decreased by increasing the thickness of the seismic mass or by reducing the density of NWs. However, it seems difficult to reach resonance frequencies lower than several kHz. A resonance frequency of 6 kHz was obtained for a density of 4 NWs/µm^2 and 100 µm thick seismic mass. While it effectively increases output power, arranging NWs into resonant arrays should not provide a large design margin in terms of resonance frequency.

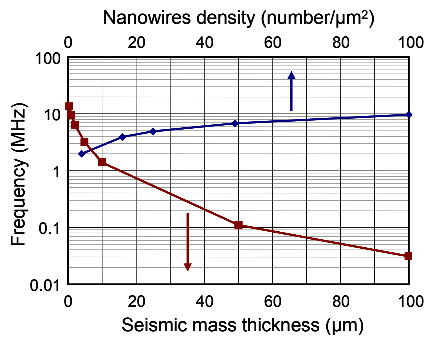

Figure 3. Resonance frequency of the structure as a function of (a) thickness of the seismic mass and (b) number of NWs per µm^2.

The general conclusion from these simulations is that the resonance frequency would remain high. Resonance-based modes are not the most appropriate at low frequency. A better approach consists in considering real-time deformations, as considered in next section.

C. Scaling rules for non resonant nanostructures

In this section, we will develop scaling rules for non resonant nanobeams, based on classical mechanics. We deliberately neglect non linear effects in this first approach, in order to derive simple analytical expressions. Our reference device is a 50 nm wide and 1 µm long ZnO NW. The scaling factor α was applied to the diameter, to the length or to both diameter and length (this case will be referred to as a change in size). In the following, we consider single clamped nanowires under bending conditions. In such conditions, the potential is mainly driven by the axial deformation associated to this bending, due to the respective values of the different piezoelectric coefficients.

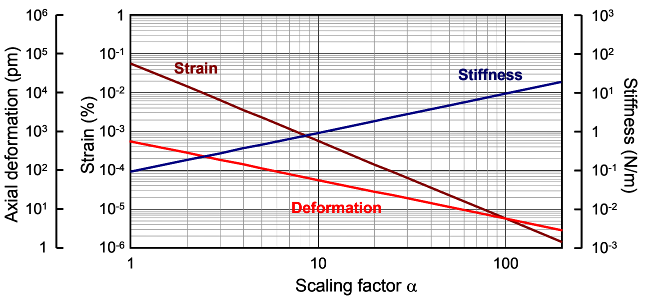

Figure 4. Effect of the size scaling down of a cantilever in terms of axial strain, axial deformation and stiffness under fixed force (80nN).

Fig. 4 shows the influence of size scaling on axial strain, axial deformation and stiffness. Stiffness, which depends on Young's modulus and geometrical parameters, is linearly decreasing as size decreases, allowing much larger strains to be reached under fixed force. This is directly beneficial to the piezoelectric potential. The associated deformation does not increase as quickly as the force is applied to a shorter beam. The main conclusion is that a smaller force is sufficient to produce a given voltage.

To evaluate the efficiency of the mechanical to electrical energy conversion of a non resonant structure, let us consider the energy variation between two, strained and unstrained, states. The mechanical energy W stored in strained state can be expressed as:

$$W = \frac{1}{2} E S^2 V \quad (2)$$

where S is the strain and V the volume [8]. The electrical energy generated in the piezoelectric material when deformed can be defined as:

$$E_c = \frac{1}{2} E^2 \frac{d_{33}^2 S^2}{\varepsilon} V \quad (3)$$

where ε is the dielectric constant. The efficiency of energy conversion (electromechanical coupling factor) can be deduced from these two equations as

$$k^2 = \frac{E_c}{W} = E \frac{d_{33}^2}{\varepsilon} \quad (4)$$

which is independent of geometrical factors. Equation (3) was used to study scaling properties of the power density for a mechanical harvesting device integrating ZnO NWs. The active area was fixed to 1 cm^2 and the overall basis thickness to 500 µm plus the length of the NWs. A homogeneous distribution of NWs was considered, with a distance equal to their diameter. For comparison with present MEMS devices, we assumed 50 mechanical deformations (not necessarily periodic) per second. The results are displayed in Fig. 5.

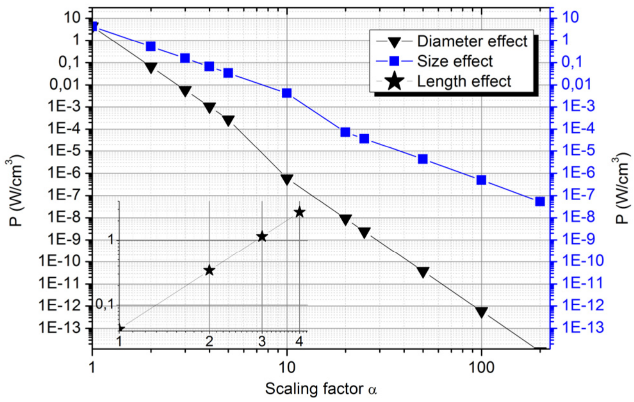

Figure 5. Power density of a mechanical energy harvesting device based on vertically integrated ZnO NWs. Effect of diameter and size scaling down (main graph) and of length scaling down (inset), with a constant force equal to 10nN or 1nN, respectively.

Nanowires size and diameter downscaling results in power density increase. The theoretical value for the smallest device (4W/cm^3 for α=1) is comparable to that of present MEMS devices, while requiring a much smaller force (10 nN is sufficient here). The corresponding power, which reaches 2 mW for one square centimetre, becomes compatible with the power needed to feed future autonomous systems. Increasing the length of the NWs also increases power density (in this case a smaller force of 1 nN was considered to remain in the small deformations regime). It should be noted that scaling down is also beneficial to reduce the overall weight.

D. Materials comparison for non resonant harvesting

Based on (4), table 2 compares typical parameters reported in the literature for some piezoelectric nanostructures, assuming that ε keeps its bulk value as a first approximation. This table shows that ZnO present the best efficiency for energy conversion. Several energy harvesting devices integrating piezoelectric nanostructures working at low frequency (<10Hz) have been reported. Vertically grown ZnO NWs have been integrated reporting up to 2.7mW/cm^3 [14], laterally integrated ZnO NWs reporting 2V@11mW/cm^3 [19]. Very recently PZT nanoribbons have been integrated laterally on a polymer and have shown the highest reported piezoelectric coefficients (Table 1) but when integrated into devices they reach 0.25V@10nW/cm^2 at 3Hz, showing clearly that integration needs to be improved.

TABLE II. EFFICIENCY OF ENERGY CONVERSION FOR DIFFERENT NANOSTRUCTURED MATERIALS. APART FOR THE DIELECTRIC CONSTANT, MATERIAL PARAMETERS ARE EXPERIMENTAL VALUES AT NANOSCALE.

Material	**Material parameter**			
	d_{33} [pm/V]	***E [GPa]***	***$\varepsilon/\varepsilon_0$ (bulk)***	***Efficiency***
PVDF	-38 [6]	0.39 [16]	13 [8]	0.005
PZT	101 [8]	46.4-99.3 [17]	300-1300 [8]	0.09-0.18
ZnO	14-26.7 [8]	100 [18]	10.9 [8]	0.2-0.7
GaN	12.8 [9]	43.9 [11]	8.9	0.09

E. Further possible improvements at nanoscale

The piezoelectric properties of nanostructures can be further improved, with resulting increase of energy harvesting efficiency. Indeed, recent qualitative measurements on 25 nm wide, 500 nm long GaN NWs featuring an 8 nm AlN barrier along their axis resulted in an estimated value of the effective piezoelectric coefficient which was 9 times larger than for their GaN intrinsic counterparts [15]. This would increase the efficiency of energy conversion by a factor 81, leading to 10 times improvement compared to ZnO. Although this theoretical prediction might be alleviated by integration details such as contact quality or process induced size dispersion [14], the use of heterostructured NWs is undoubtedly opening very interesting prospects.

IV. CONCLUSIONS

Because of their improved properties, such as enhanced piezoelectric coefficients and reduced stiffness, piezoelectric nanostructures are a promising solution for mechanical energy transduction into electrical energy. This can be used to harvest mechanical energy from environment in the perspective of feeding autonomous systems, as well as for sensing applications.

It has been shown however that for low frequency applications, nanostructures should not be operated in the resonant or close to resonance modes, and should rather be operated in real-time deformation mode. This is important for wearable applications or structural health monitoring, where mechanical inputs are random or at very low frequency (from fractions of Hz to kHz). Each single deformation event is then generating a small amount of energy. It should be noted that the force needed to induce a deformation is decreasing with device downscaling so that the probability of such events is increasing. It has been shown that the energy provided by an array of NWs could be compatible with the power needed to feed future autonomous systems. Using heterostructured NWs can further increase the energy conversion efficiency.

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