

# A HYBRID ELECTRODYNAMIC VIBRATION HARVESTER

T. Sterken<sup>1,2</sup>, P. Fiorini<sup>1</sup>, C. Van Hoof<sup>1,2</sup>, R. Puers<sup>2</sup>

<sup>1</sup>IMEC vzw, Leuven, Belgium

<sup>2</sup>ESAT, Katholieke Universiteit Leuven, Leuven, Belgium

**Abstract:** A vibration harvester has been designed, combining an electrodynamic transducer with a micromachined resonator. The transducer consists of 8 *off-the-shelf* NdFeB magnets floating above a series of copper coils. The coils are shaped in a meander to optimize the coupling factor of the generator. The suspension of the magnets is tuned to invoke resonance at the frequency of the targeted vibration, while the inertia of the magnets is used to improve the energy extraction within a volume of 0.3 cm<sup>3</sup>. A prototype has been designed for 1g vibrations at 100 Hz.

**Key Words:** NdFeB, vibration, harvester

## 1. INTRODUCTION

Miniature vibration harvesters are being developed as an alternative to storage based energy supplies for autonomous electronic systems, such as wireless sensor nodes or mobile detectors [1,2]. At present storage based systems, such as batteries, provide a robust solution, but their lifetime decreases with their size (and weight). Miniature systems will thus have a short lifetime. Furthermore replacing batteries in autonomous systems is often not economical, and sometimes even impossible.

The alternatives provided by powerMEMS tackle this contradiction either by improving the energy density of the storage medium (e.g. in micro-fuel cells), either by extracting energy from the ambient of the autonomous system. The energy source that is used depends on the application, ranging from mechanical energy (vibration, motion) to thermal energy (body heat) or solar energy. The power necessary for operating autonomous systems has decreased over time down to a level of 50  $\mu$ W.

The harvester proposed in this paper is designed for vibrations around human activities, by tapping into a harmonic mode of the electrical grid (e.g. 100 Hz in Europe, 120 Hz in U.S.A.).

Vibration harvesters consist of a transducer that converts the mechanical power in the motion of the vibrating object with respect to a non-vibrating reference. It is however not always feasible to connect a miniature autonomous system to an external reference. An internal reference is then created using the inertia of a

seismic mass to transfer the motion of the vibration towards the energy transducer. A mass with a higher inertia will provide a better reference. The following paradox resides in the use of miniature vibration harvesters: the output power of the harvester decreases as the dimensions of the device scale down. As a result their size is always in the mm range.

Nevertheless miniature harvesters make use of micromachining and MEMS, because of the precision, yield and reliability that can be obtained. A micromachined harvester furthermore allows a possible integration of the circuitry of the system into a single system-in-a-package [2]. The electrodynamic harvester presented in this contribution combines the advantages of microfabrication with the benefits of millimeter scale components.

## 2. DESIGN

Vibration harvesters have been analyzed extensively in literature [3,4,5]. Although some discussion remains on the optimization strategy, the following design rules are generally accepted.

### 2.1 Mechanical Design

The mechanical design of a harvester deals with the coupling of the motion of the vibration to the mechanical port of the transducer. The mechanical port of the transducer is connected to the vibrating package and the seismic mass. To reduce damping the mass  $m$  is suspended in the harvester. The suspension itself however shows a spring-like behavior, resulting in resonance at the natural frequency  $\omega_n$ .

The maximum mechanical power that can be extracted by the mechanical system at resonance is given by [4,5]:

$$P_{\max} = \frac{1}{2} m \omega_n a x_{\max} \quad (1)$$

In this formula the maximum allowed displacement of the mass relative to the package,  $x_{\max}$  is taken into account, for a given vibration with pulsation  $\omega_n$  and acceleration  $a$ . This power increases linearly with the size of the seismic mass. A seismic mass with a higher inertia will allow the designer to extract more energy from the vibration, while resonance can be used to match the small amplitudes or forces of the vibration to the needs of the transducer.

## 2.2 Transducer Design

The transducer is the key component of the energy harvester. An optimal design matches the mechanical impedance of the transducer to the characteristics of the mass-spring system. Likewise, its electrical impedance is matched to the specifications of the power electronics of the autonomous system. Although different types of electromechanical transducers exist [6], their working principles coincide: energy is stored in the electric field or in the magnetic flux. A change in geometry will then result in a change of stored energy, at the expense of the mechanical energy needed to alter the geometry.

The electrodynamic transducer presented in this work uses the energy stored in the flux  $\mathbf{B}$  of a permanent magnet. This flux is coupled to the electric circuit by a coil (Fig. 1), a change in geometry will induce a change in the coupled flux  $\phi$ , which in turn will generate an e.m.f. across the coil:

$$\begin{aligned} e.m.f. &= -\frac{d\phi}{dt} = -\frac{d}{dt} \oint_A \mathbf{B} ds \\ &= -NB \frac{dA}{dt} = -NB \frac{dA}{dz} \dot{z} \end{aligned} \quad (2)$$

In equation (2) the coupled area  $A$  changes over time as the mechanical configuration changes. The velocity of the mass is indicated by  $\dot{z}$ . The current  $i$  that is induced through the electric load  $R$  by the e.m.f. will in turn induce a counteracting force on the magnet. The factor  $\Gamma = NB \frac{dA}{dz}$  defines the ratio between the speed of the mass and the generated voltage.

An optimal transducer is designed in such a way to electromechanically damp the motion of the mass to its maximum displacement  $x_{\max}$ , when the input impedance  $R$  of the power electronics is applied. The mechanical damping factor needed to reach the power of equation (1) is given by:

$$\zeta_s = \frac{\Gamma^2}{2Rm\omega_n} = \frac{a}{2\omega_n^2 x_{\max}} \quad (3)$$

The optimal transformation factor follows:

$$\Gamma = \sqrt{\frac{aRm}{\omega_n x_{\max}}} \quad (4)$$

## 2.3 Design of the harvester

In order to optimize the generated power at a frequency of 100 Hz, the seismic mass has to be maximized within the small volume of the generator. The NdFeB magnets have a density of 7400 kg/m<sup>3</sup> as opposed to the density of silicon (2300 kg/m<sup>3</sup>). They are incorporated on the seismic mass. This is achieved by etching pockets in the mass (Fig. 2).

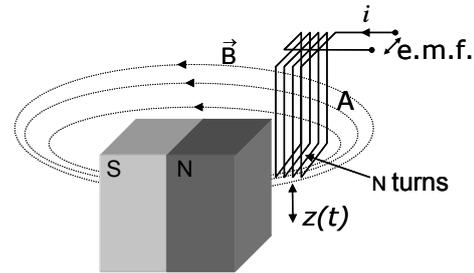


Fig. 1: Electromagnetic transduction mechanism used in the vibration harvester.

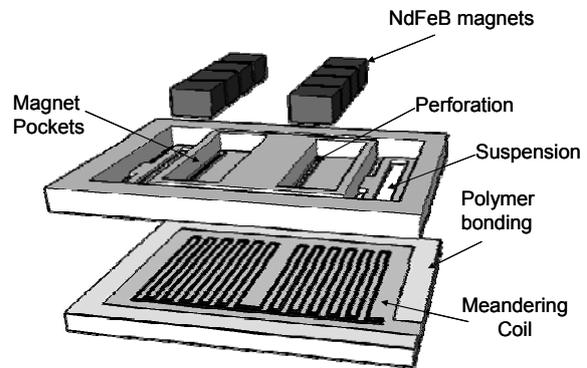


Fig. 2: Exploded view of the proposed device

In this way the mass is increased from 40 mg up to 80 mg. The suspension of the mass is shaped in order to obtain a spring constant of 33 N/m.

The magnets are *off-the-shelf* components of 1 mm<sup>3</sup>, with a residual flux density of 1.2 T [7].

The pockets that hold the magnets are perforated at the position of the poles of the magnets. The flux lines are slightly condensed due to the diamagnetic character of silicon.

Underneath the floating mass a coil has been patterned on the bottom wafer. This coil has a meandering shape: the coupled flux of the magnet to the coil changes every time the poles of the magnet cross the meandering metal line. The result is an increase of the transformation factor  $T$  by increasing the factor  $dA/dz$ .

As a consequence the frequency of the generated signal will be a multiple of the input frequency. The same approach has been used in literature for electrostatic vibration harvesters [5,8] and piezoelectric harvesters [9]. The meandering copper coil can be wound several times to further increase the transformation factor (factor  $N$  in equation (2)). Based on equation (1) the maximum achievable mechanical power is estimated up to 200μW for a 1g vibration at 100Hz.

### 3. PROCESS FLOW

The prototyping of the vibration harvester is based upon the same process flow already used for electrostatic generators [5].

The device consists of 3 wafers, of which the top wafer only serves as a cap for the device. Pyrex glass was selected as material for the bottom wafer, for demonstration purposes. The thermal match between silicon and Pyrex is a necessity to minimize stresses after bonding. At first a 300 nm copper layer is deposited on the wafer and subsequently patterned in the meandering shape.

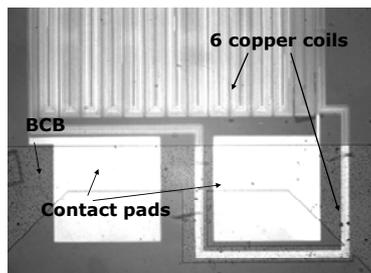


Fig. 3: Top view of the bottom wafer, illustrating the 6 meandering copper coils.

As this prototype is intended as a proof of concept, its design and fabrication have been simplified, at the expense of a loss in performance. Only one metal layer was deposited, while the copper coil was wound 3 to 6 times to increase the transformation factor (Fig. 3). In a next step the BCB is spun and patterned on the wafer, which will later be used for polymer bonding of the wafers.

After realization a series impedance of 3.3kΩ was measured (6 windings), while the inductance was limited to 200 μH. This wafer is next diced halfway its thickness. In this way the wafer can still be processed as a whole, while dicing can be done manually by snapping across the pre-diced lines. The middle wafer consists of silicon that has been coated with a 150 nm Si<sub>3</sub>N<sub>4</sub> layer on both sides. This layer is patterned with the springs and perforation holes. Next the wafer is etched in KOH (35% at 50°C), where the Si<sub>3</sub>N<sub>4</sub> layer was used as a hard mask. Although this step could as well be performed using DRIE, KOH was chosen as a fast alternative for prototyping. The springs are then oriented along the {100} direction (Fig. 4). The combination of a 30 μm wide and 15 μm high folded beam of 2.3 mm should result in a resonance frequency of 100 Hz, while allowing a displacement of 800 μm.

The two wafers are next bonded by a 3000 N force at 250 degrees. The BCB bond is now KOH-resistant, and the glass wafer protects the freshly etched springs. After patterning the top side of the waferstack, the masses and magnet pockets are etched, again by 35% KOH, until a membrane of 30 μm remains. Finally the devices are released in a short DRIE-etch step. The magnets are manually mounted, and glued to the top of the mass.

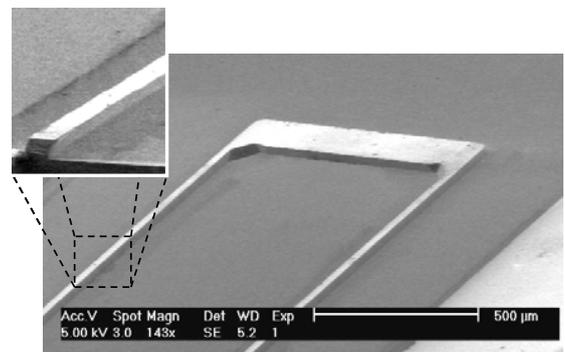


Fig. 4: The springs are etched in KOH. Due to their {100} orientation a 90° angle was obtained

#### 4. DISCUSSION

The device as presented has not been optimized, neither in reliable fabrication nor in optimal matching towards power electronics circuitry, until the concept has been proved to work. As a result many improvements can be found for optimization of the power output.

A first improvement would be to increase the number of coil windings  $N$  in order to obtain a better coupling, while the thickness of the copper layer could be increased to manage the parasitic series resistance of the coil. This measure could be extended towards depositing multiple layers of coils on the glass wafer, each insulated by e.g. BCB. A second improvement consists in filling the perforated holes with a ferromagnetic material (e.g. Ni) for a better guiding of the magnetic flux towards the coils. As a result the pitch of the meandering coil can be further decreased and the transformation factor is further increased.

#### 5. CONCLUSIONS

A prototype of an electrodynamic vibration harvester has been designed and fabricated. Through the use of  $1 \text{ mm}^3$  NdFeB magnets in the seismic mass of the generator the mechanical capturing of energy has been improved at 100 Hz.

#### REFERENCES

- [1] T. Torfs, V. Leonov, C. Van Hoof, B. Gyselinckx, Body-Heat Powered Autonomous Pulse Oximeter, *5th IEEE Conference on Sensors*, 2007, pp. 427-430.
- [2] V. Pop, R.J.M. Vullers, D. Hohlfeld, J. De Boeck, Wireless Autonomous Transducer Solutions for Hybrid Electrical Vehicle Applications, *Proceedings of the International Conference on Ecologic Vehicles & Renewable Energies*, 2007.
- [3] S.P. Beeby, M.J. Tudor, N.M. White, Energy Harvesting Vibration Sources for Microsystems Applications, *Journal on Measurement Science and Technology*, 17, 2006, R175–R195.
- [4] P.D. Mitcheson, T.C. Green, E.M. Yeatman, A. S. Holmes, Architectures for Vibration-Driven Micropower Generators, *Journal of MEMS*, vol. 13, no. 3, 2004, pp. 429-440.
- [5] T. Sterken, P. Fiorini, G. Altena, C. Van Hoof, R. Puers, Harvesting energy from Vibration by a Micromachined Electret Generator, *Digest Tech. Papers Transducers'07 Conference*, Lyon, 2007, pp. 129-132.
- [6] T. Sterken, K. Baert, C. Van Hoof, R. Puers, G. Borghs, P. Fiorini, Comparative Modelling for Vibration Scavengers, *3d IEEE Conference on Sensors*, 2004, pp. 1249-1252
- [7] <http://www.powermagnetshop.de>
- [8] T. Sterken, P. Fiorini, K. Baert, G. Borghs, R. Puers, Novel Design and Fabrication of a MEMS Electrostatic Vibration Scavenger, *Tech. Digest PowerMEMS 2004*, Kyoto, pp. 18-21
- [9] G. Despesse, J.J. Chaillout, T. Jager, F. Cardot, A. Hoogerwerf, Innovative Structure for Mechanical Energy Scavenging, *Digest Tech. Papers Transducers'07 Conference*, Lyon, 2007, pp. 895-898
- [10] D.-G. Lee, G.P. Charman, D. Murphy, C. Schulenburg, Novel Micro vibration Energy Harvesting Device Using Frequency Up Conversion, *Digest Tech. Papers Transducers'07 Conference*, Lyon, 2007, pp. 871-874