A low frequency MEMS energy harvester scavenging energy from magnetic field surrounding an AC current-carrying wire

2016 J. Phys.: Conf. Ser. 757 012039

(http://iopscience.iop.org/1742-6596/757/1/012039)

Journal of Physics: Conference Series **757** (2016) 012039 doi:10.1088/1742-6596/757/1/012039

A low frequency MEMS energy harvester scavenging energy from magnetic field surrounding an AC current-carrying wire

Oskar Z. Olszewski, Ruth Houlihan, Alan Mathewson, Nathan Jackson

Tyndall National Institute, University College Cork, Cork, Ireland

zbigniew.olszewski@tyndall.ie

Abstract. This paper reports on a low frequency piezoelectric energy harvester that scavenges energy from a wire carrying an AC current. The harvester is described, fabricated and characterized. The device consists of a silicon cantilever with integrated piezoelectric capacitor and proof-mass that incorporates a permanent magnet. When brought close to an AC current carrying wire, the magnet couples to the AC magnetic field from a wire, causing the cantilever to vibrate and generate power. The measured average power dissipated across an optimal resistive load was 1.5 μW. This was obtained by exciting the device into mechanical resonance using the electro-magnetic field from the 2 A source current. The measurements also reveal that the device has a nonlinear response that is due to a spring hardening mechanism.

1. Introduction

In recent years, much attention has been placed on the Internet of Things (IoT) [1]. The IoT refers to a large number of nodes, also called “things” that exchange the data wirelessly across the network. The individual nodes are typically powered by batteries with limited lifetime and currently the IoT urges for development of energy-autonomous nodes and energy harvesting is a key technology addressing such a demand [2, 3]. Multiple energy sources are available within the environment e.g. light, mechanical vibrations, electromagnetic fields, etc., and these can be converted into useable electrical power by means of various transduction methods, including photovoltaic, thermoelectric, electrostatic, and piezoelectric. Because of their numerous advantageous, vibrational piezoelectric harvesters have received much attention [3-8]. A key challenge of vibrational harvesters is that the devices typically resonate with a narrow frequency bandwidth. This is a major problem because the frequency of the vibration source may vary over time and, as a result, the power generation drops significantly. Many solutions to broaden the bandwidth of vibrational harvesters have been investigated. The bandwidth can be broadened by mechanical tuning of the device stiffness [9], connecting of multiple devices [10, 11], introducing a nonlinearity to the device behavior [12-17]. An alternative approach to bandwidth broadening is to select an application that provides a stable source of vibration [18-20]. One such source is the AC magnetic field surrounding an AC current-carrying wire such as the power mains of electrical equipment. In this paper, we report on a piezoelectric harvester that scavenges energy from an AC current-carrying wire. In previous work [18-20] a similar concept was shown; however the device was a macro-scale assembly to enable a low frequency operation (≈50 – 60 Hz). In this work, we demonstrate a smaller device fabricated in MEMS process that also operates at low frequency.

2. Device Concept, Description and Fabrication Process

2.1. Device Concept

A general concept used in this work is described in Figure 1 and has been proposed by Leland et al. [18]. The device consist a permanent magnet attached to the free-end of a piezoelectric cantilever with the magnetization direction aligned with the mechanical compliance direction of the cantilever. When the cantilever is brought in close proximity to an AC current-carrying wire the magnet couples to the AC magnetic field from the wire. The force acting on the magnet is proportional to the integral of the field gradient over the magnets volume [20-22]. This, in the most general form, can be described as:

$$F_M = B_r \int \frac{d(H_z)}{dz} dV \, , \tag{1}$$

where F_M is the vertical force acting on the magnet, B_r is the vertical remanence of the magnet, V is the magnet volume, and H_z is the vertical component of the magnetic field that, at a given distance from the wire, is proportional to the current magnitude. Since F_M is an alternating force, the cantilever vibrates at the frequency of the current and with a displacement that is proportional to its magnitude.

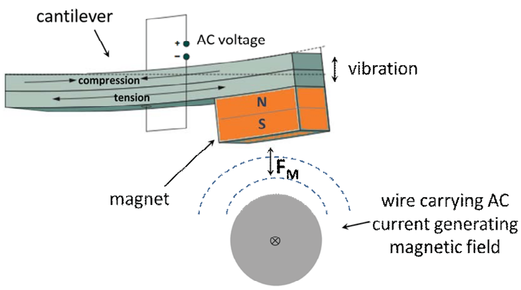

Figure 1. Schematic diagram of a device concept in this work.

From equation 1 it can be concluded that in order to maximize the coupling force F_M for a given remanence, magnet volume and current, the field gradient must be maximized. The studies [20, 22] showed that when coupling to a single-wire cord, the field gradient is maximized along a 45° line from the centre of the wire, whereas in case of a double-wire cord, the maximum gradient occurs above the cord centre. The vibrating piezoelectric cantilever acts as a transducer, whereby the induced stress and strain along the cantilever generates an electric potential across the material thickness, e.g. during displacement upwards the top part of the cantilever is under compression while the bottom part is under tension and vice versa for the downward displacement. This is a common operation mode (31) of piezoelectric cantilever-based harvesters. The voltage generated from the harvester depends on the exact geometry of the device and on the effective material properties. In general however, it increases with the mechanical strain developed in the piezoelectric film along the device length. This strain is proportional to the device displacement which depends on the magnitude of the excitation force (F_M) and which can be maximized by driving the device into mechanical resonance [7, 22-24].

2.2. Device Description and Fabrication Process

Figures 2(a), (b) and (c) show the top-view, bottom-view and cross-sectional view of the device respectively. The harvester is comprised of a thin device silicon cantilever that supports an extended silicon mass. On the top surface of the cantilever, the piezoelectric capacitor is formed of a titanium (Ti) bottom electrode, an aluminium nitride (AlN) piezoelectric layer, and an aluminium (Al) top electrode. As described above, the capacitor converts the mechanical vibration into a voltage that can be measured across the capacitor. The total length of the device is 10 mm and that includes a 1.5 mm cantilever and 8.5 mm mass. The width of the device is 7 mm and the cavity etched in the mass is 6.5

mm along the device length by 5 mm along the width. The harvesters were fabricated from an SOI wafer with a 17 μm thick device silicon layer, a 1 μm thick buried oxide, and a 535 μm thick bulk silicon. Details of the fabrication process were described elsewhere [25].

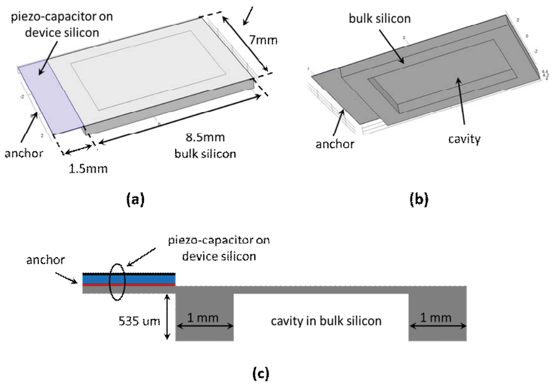

Figure 2. Schematic representation of the harvester (b) top-view, (b) bottom-view, and (c) cross-sectional view.

Figure 3(a) illustrates the top-view of the device attached to a PCB. The bottom-view with the assembled magnet is shown in Figure 3(b). Future devices will use an integrated micro-magnet which will be deposited in the cavity of the mass [26]. For the purposes of concept demonstration, a commercial permanent neodymium magnet (*Br* = 1.3) was used here.

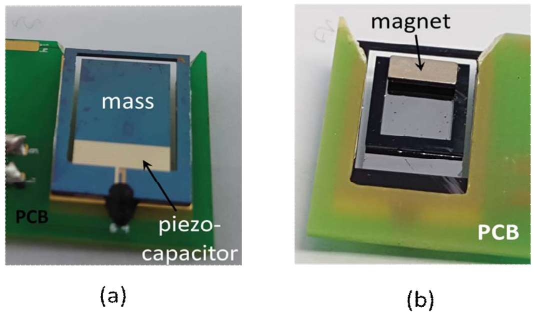

Figure 3. Photograph of the device, (a) top-view, (b) bottom-view.

3. Experimental Results and Discussion

3.1. Initial Characterisation

The first resonance of the device, before and after the magnet assembly was measured using Laser Doppler Vibrometry (LDV). The device was excited into vibration by applying a mechanical shock pulse to the clamp holding the device PCB under the vibrometer head. The test results along with the simulated values are summarized in Figure 4(a). The simulated values of resonance frequency were obtained using a modal analysis in Comsol (model shown in Figure 2). The default material properties in Comsol for silicon and AlN were used. The model assumed a 535 μm thick bulk silicon, a 5 x 2.0 x 0.5 mm^3 magnet volume and a 7500 kg/m^3 magnet density. The thicknesses of the device silicon and AlN layer used in the model were 15 μm and 0.4 μm (values measured using SEM). The metal layers and silicon nitride were not considered during simulation. Figure 4(a) shows the measured resonance of the device before and after the magnet was attached. The results show that the resonance drops from around 75 Hz to 39 Hz due to added mass of the magnet. This agrees well with the results obtained from the model.

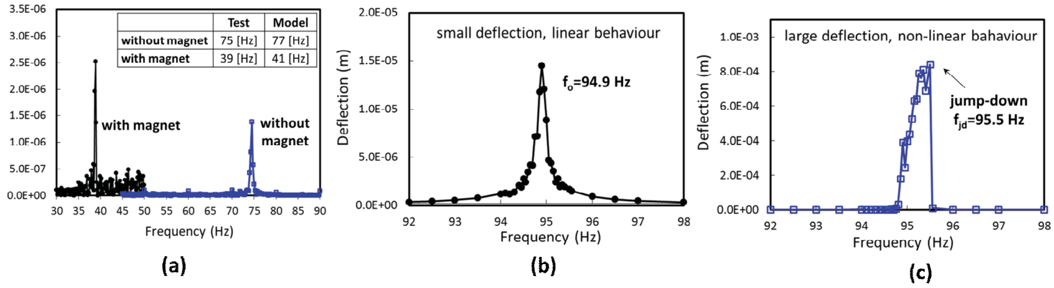

Figure 4. (a) The resonance curve with and without a magnet, (b) resonance curve at small displacements and (c) resonance curve at large displacements.

Figures 4(b) and 4(c) show the measured displacement of a device similar to that described above but without the piezoelectric capacitor and with no permanent magnet. This all-silicon device can therefore be considered a purely mechanical test structure. The thickness of the device silicon was 20 μm and the total length was 8.2 mm with the beam and mass lengths equaling 1.2 mm and 7 mm, respectively. The device was excited by a mechanical shaker into two distinct vibration levels. When the device vibrates with low deflections relative to the thickness of the cantilever, the response is linear and symmetrical around a single frequency of 94.9 Hz. In contrast, as can be seen in Figure 4(c), when the device vibrates with large deflections, the response of the device is nonlinear and asymmetrical about the center frequency: the deflection increases steadily from linear resonance of 94.9 Hz before it jumps down at 95.5 Hz. This is a typical characteristic of a resonator exhibiting spring hardening and can be modeled by a spring element featuring a cubic term in its force-displacement relationship as [16, 17, 27-30]

$$F = F_b + F_s \approx k_b x + k_s x^3, \tag{3}$$

where F_b is the linear spring component due to the bending strain in the beam that dominates the device stiffness at low displacements and F_s is the nonlinear spring component due to the stretching strain that comes into play at large displacements. The k_b and k_s are the linear and nonlinear spring constants, respectively and x is the displacement. In such a system, the stretching strain causes the spring hardening whereby the stiffness of the cantilever increases and shifts the resonance frequency to the right, as in Figure 4(c). The full solution of Duffing equation [29] reveals that resonators with nonlinear compliance feature a hysteretic frequency response that depends on whether the frequency is being increased or decreased. The harvesters in this work operate with displacements in the range of millimeters and the mechanical nonlinearity is also evidenced on the device electrical characteristics.

3.2. Electrical Test Setup and Experimental Results

In the experiments a custom-built AC current source was used capable of supplying the AC current of various frequencies and amplitudes. Figure 5 shows the image of the device under test. As explained in [20, 22], to maximize the device displacement and charge generation, the device in its rest position is located such that the magnet is at the angle of approximately 45^{o} with respect to the wire center.

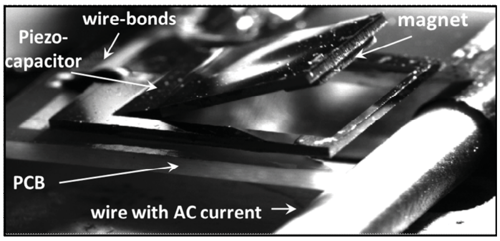

Figure 5. The device image taken with a high speed camera during operation when it is displaced upwards.

To evaluate the average power from the harvester, the RMS current, in a resistive optimal load of 2 MΩ was measured versus the frequency of the source current of 2 A (RMS). This level of source current actuated the device to the peak amplitude of 3 mm. The frequency sweep-up and sweep-down were performed and results are shown in Figure 6(a). The average power shown in Figure 6(b) was calculated according to the formula $P_{RMS} = I_L^2 \times R_L$. It can be seen that the electrical characteristics of the harvester have strong nonlinear behavior due to nonlinear mechanical spring as observed on structure in Figure 4(d). From the sweep-up data, the power increases steadily with the source frequency up to the peak value of approximately 1.5 μW at frequency of 42.3 Hz, after which the power suddenly drops. This is the jump-down frequency at which the feedback from the stretching strain that causes the beam stiffening can no longer compensate for the increase in the source frequency. By considering the sweep-down response of the device, it is evident that the full characteristic has the hysteresis typical for the Duffing resonators [16, 17, 27-30].

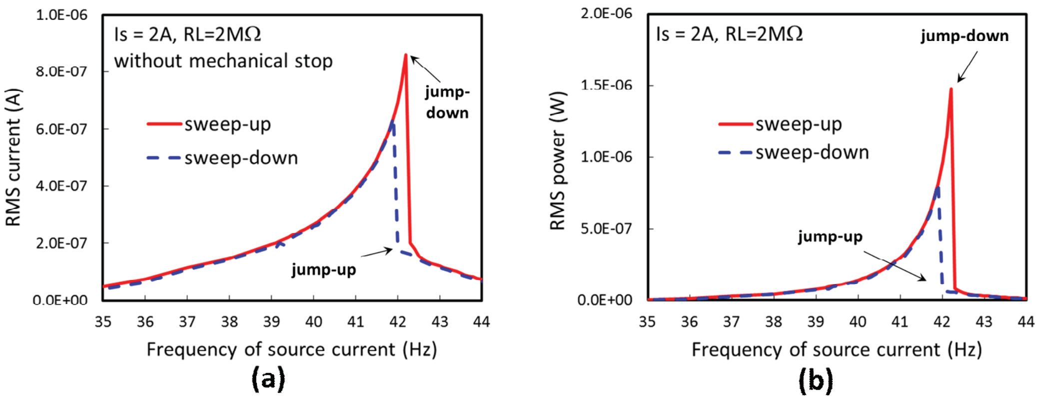

Figure 6. (a) RMS current measured in the load, (b) RMS power calculated from the measured current.

4. Conclusions and future work

This paper has described a MEMS piezoelectric energy harvester that targets scavenging the energy from the magnetic field surrounding a power line. The device concept, fabrication and test results were presented. To maximize the generated power the device was tested such that its mechanical resonance matches the frequency of the source current. The results revealed that the harvester has a nonlinear mechanical compliance and the average power output of 1.5 μW at 2 A of source current. Further characterisation of the devices should be performed in order to understand the device performance in terms of frequency bandwidth, stability around the jump-down frequency, and reliability. It is anticipated that incorporation of mechanical stops as proposed in earlier studies could broaden the frequency response of the device leading to better device stability, and this will be investigated in subsequent research.

Acknowledgements

The authors would like to thank Enterprise Ireland and Analog Devices for supporting this research.

References

[1] M. H. Miraz, et al., "Review on Internet of Things (loT), Internet of Everything (IoE) and Internet ofNano Things (IoNT)", ITA 2015, Wrexham, 8-11 Sept. 2015, 219 - 224.
[2] R. J. M. Vullers, et al., "Energy Harvesting for Autonomous Wireless Sensor Networks, IEEE Slid-State

Circuits Magazine, Spring 2010, 29-38.
[3] S. Kim, et al., “Ambient RF Energy-Harvesting Technologies for Self-Sustainable Standalone Wireless Sensor platforms “, Proc. of IEEE, Vol. 102, No. 11, Nov. 2014, 1649 – 1666.
[4] S-G. Kim, et al., S. Priya, I. Kanno, “Piezoelectric MEMS for energy harvesting”, Material Research Society Bulletin, Vol. 37, November 2012, 1039 – 1050.
[5] H. Li, et al., “Energy harvesting from low frequency applications using piezoelectric materials”, Applied Physics Reviews 1, 041301 (2014).
[6] P. D. Mitcheson, et al., “Energy Harvesting From Human and Machine Motion for Wireless Electronic Devices” Proc. of IEEE, 96, No. 9, 2008, 1457 – 1486.
[7] S. Roundy, et al., “A piezoelectric vibration based generator for wireless electronics, Smart Mater. Struct., 13 (2004) 1131–1142.
[8] C-B. Eom, et al., “Thin-film piezoelectric MEMS”, Material Research Society Bulletin, Vol. 37, November 2012, 1007 – 1017.
[9] Y. Hu, et al., “A piezoelectric power harvester with adjustable frequency through axial preloads,” Smart Mater. Struct., Vol. 16, No. 5, Oct. 2007, 1961 – 1966.
[10] Z. Yang, “Connected Vibrating Piezoelectric Bimorph Beams as a Wide-band Piezoelectric Power Harvester”, Journal of Intell. Mater. Syst. Struct., Vol. 20, No. 5, November 2008, 569 – 574.
[11] S. M. Shahruz, “Design of mechanical band-pass filters for energy scavenging”, Journal of Sound and Vibration, Vol. 292, No. 3–5, May 2006, 987 – 998.
[12] L. Gammaitoni, et al., “Nonlinear oscillators for vibration energy harvesting”, Appl. Phys. Lett. 94, 164102 (2009).
[13] F. Cottone, et al., “Nonlinear energy harvesting”, Physics Review Letters, 102, 080601, (2009).
[14] V. R. Challa, et al., “A vibration energy harvesting device with bidirectional resonance frequency tenability, Smart Mater. Struct., 17 (2008) 015035 (10pp).
[15] M. S. M. Soliman, et al., “A wideband vibration-based energy harvester” J. Micromech. Microeng. 18 (2008) 115021 (11pp).
[16] A. Hajati, et al., “Ultra-wide bandwidth piezoelectric energy harvesting”, Appl. Phys. Lett. 99, 083105 (2011).
[17] A. Hajati, et al., “Wide-bandwidth MEMS-scale piezoelectric energy harvester”, PowerMEMS'09, Washington DC, USA, December 1-4, 2009.
[18] E. S. Leland, et al., “Energy scavenging power sources for household electrical monitoring”, Micro and Nanotechnology for Power Generation and Energy Conversion Applications, USA, Nov. 29, 2006.
[19] W. He, et al., “Energy harvesting from electric power lines employing the Halbach arrays”, Rev. Scient. Instr. 84, 105004 (2013).
[20] I. Paprotny, et al., “Electromechanical energy scavenging from current-carrying conductor”, Sensors, Vol. 13, No. 1, January 2013.
[21] B. Wagner, et al., “Microfabricated actuator with moving permanent magnet”, Micro Electro Mechanical Systems, MEMS’91, 30 January - 2 February, Nara, 1991.
[22] E. S. Leland, at al., “A MEMS AC current sensor for residential and commercial electricity end-use monitoring”, J. Micromech. Microeng. 19 (2009) 094018 (6pp).
[23] H. Liu, at al., “Piezoelectric MEMS Energy Harvester for Low-Frequency Vibrations With Wideband Operation Range and Steadily Increased Output Power”, JMEMS, Vol. 20, No. 5, October 2011.
[24] T. M. Kamel, at al., “Modeling and characterization of MEMS-based piezoelectric harvesting Devices”, J. Micromech. Microeng. 20 (2010) 105023 (14pp).
[25] N. Jackson, at al., “Influence of aluminium nitride crystal orientation on MEMS energy harvesting device performance”, J. Micromech. Microeng. 23 (2013) 075014 (9pp).
[26] N. Jackson, at al., “Integration of Thick-Film Permanent Magnets for MEMS Applications”, JMEMS, 14 June 2016.
[27] R. Ramlan, at al., “On the performance of a dual-mode non-linear vibration energy harvesting device”, Journal of Intelligent Material Systems and Structures, 0(0) 1–10, 2012.
[28] G. Gafforelli, et al., “Experimental verification of a bridge-shaped, non-linear vibration energy harvesters”, Appl. Phys. Lett. 105, 203901 (2014).
[29] S. G. Buttow, et al., “A resonant generator with non-linear compliance for energy harvesting in high vibrational environment”, International Electric Machines & Drives Conference, Antalya, 3-5 May 2007.
[30] D. Mallick, et al., “Interplay between electrical and mechanical domains in a high performance nonlinear energy harvester”, Smart Mater. Struct., 24 (2015) 122001 (9pp).