MEMS ELECTRODYNAMIC VIBRATIONAL ENERGY HARVESTERS USING MULTI-POLE MAGNETIC ARCHITECTURES

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Abstract: A multi-pole magnetic architecture is presented for electrodynamic vibration energy harvesting at MEMS scale. The device is fully microfabricated and comprises a magnetic array formed using a bonded powder technique with an electrical coil on an in-plane-vibrating silicon paddle. The coil is patterned in a serpentine fashion such that each alternating coil segment aligns with either an upward or downward magnetic field, resulting in 12 magnet/coil pairs or poles. At its natural frequency of 5 kHz, the harvester open-circuit voltage increases linearly from 8 μV to 32 μV for accelerations ranging from 1 g to 4 g, respectively. The corresponding average power output of the device at its optimal load resistance of 1.5 Ω ranges from 9.3 pW to 171 pW for these acceleration levels.

Keywords: Energy harvesting, micro magnets, magnetic devices, electrodynamic coupling.

INTRODUCTION

There is ongoing interest in MEMS-scale energy harvesting devices to power wireless sensors and other low-power electronics [1]. While electrodynamic (permanent magnet/coil) transduction is competitive with other transduction mechanisms at the macroscale, there exists two key challenges that hinder its development at the micro scale.

First, there exists a challenge in fabricating and integrating permanent magnets in MEMS processes. Most of the small-scale electrodynamic energy harvesters built to date are not fully microfabricated. Examples include devices presented by Kulkarni *et al.*, [1] Sari *et al.*, [2] and Wang *et al.*, [3] etc., which all use some combination of micro- and macro-fabricated parts. Recently, there have been advances in fabricating high-performance micro magnet arrays using bonded-powder [4], sputtering [5] and laser micromachining techniques [6]. These techniques facilitate fully microfabricated electrodynamic energy harvesters such as the harvester presented by Wang *et al.* using a bonded-powder magnet [7], and another with integrated NdFeB micro-magnets presented by Jiang *et al*. [8].

The second challenge in developing electrodynamic energy harvesters at the microscale is their generated voltage output. The output voltages of traditional single-magnet/single-coil electrodynamic harvester architectures are generally too low for efficient rectification and amplification. Higher voltages are desired to enable easier power processing to store the harvested energy. While voltage enhancement can be achieved by adding additional turns to the coil, this adds electrical resistance to the system and may inhibit power and power density. In addition, multi-turn, spiral-like coils typically require two metal layers to access the innermost windings, thus adding fabrication complexity.

Shuo *et al*. [9] have demonstrated that multi-pole design architectures can increase the voltage output without sacrificing the power output, compared to single-pole designs. Recent work presented by Jiang *et al*. [8] also explores multi-pole magnet design for energy harvesting. However, they utilized discrete multi-turn coils underneath each magnet pole. In this paper, a multi-pole magnetic architecture with a continuous, single-turn serpentine (wave-like) winding is explored.

DEVICE DESIGN

The prototype device is designed with a fixed array of six permanent magnets that creates a spatially undulating magnetic field of 12 poles. The magnet array faces a lateral vibrating cantilever beam with a coil on the surface, as shown in Fig. 1.

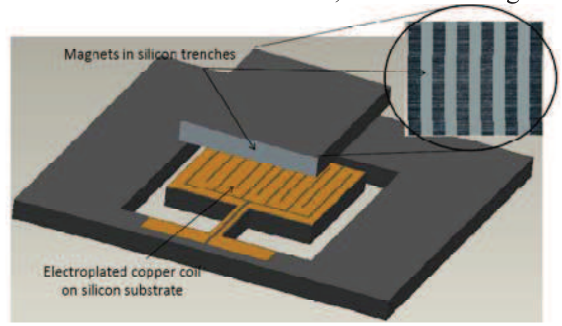

Fig. 1: Schematic of electrodynamic vibrational energy harvester with multi-pole architecture.

The cantilever beam is designed in silicon to obtain in-plane vibrations with high mechanical quality factor. The coil needed for transduction is electroplated on the surface of the vibrating beam.

The coil is designed in a serpentine configuration (also known as a wave winding) such that each alternating coil segment aligns with either an upward or downward magnetic field, forming multiple magnet-coil pairs. With the vibration of the beam, each coil segment is subjected to an appropriately oriented magnetic field, so that all coil segments work together constructively to form the total output voltage. In other words, the net voltage from the harvester is sum of the individual voltages from each coil segment.

The working principle of the electrodynamic energy harvester relies on the Faraday's law of induction. Considering a constant out-of-plane magnetic field from the magnet and the coil is displaced perpendicularly (in-plane) to the field at a velocity dx/dt, the open-circuit voltage induced in any given coil segment is given by

$$V_C = Bl\frac{dx}{dt}, \tag{1}$$

where B is the average out-of-plane magnetic flux density acting on that given coil segment from the magnet, and l is the length of the coil segment. Since the coil is designed such that each segment of the serpentine coil is aligned with either the bonded "magnet" or "no magnet" region, as shown in Fig. 2, the net voltage V_{net} induced in the coil is the sum of the voltages induced in each segment, and is given by

$$V_{net} = \left(N_1 B_1 + N_2 B_2\right) l \frac{dx}{dt}, \tag{2}$$

where N_1 and N_2 are the number of coil segments over the "magnet" and "no magnet" regions, and B_1 and B_2 are the corresponding average magnetic flux densities acting on each coil segment. The resulting time-average power output of the energy harvesting device with matched electrical load R_{load} is given by

$$P_{out} = \frac{\left|V_{net}\right|^2}{4R_{load}}. \tag{3}$$

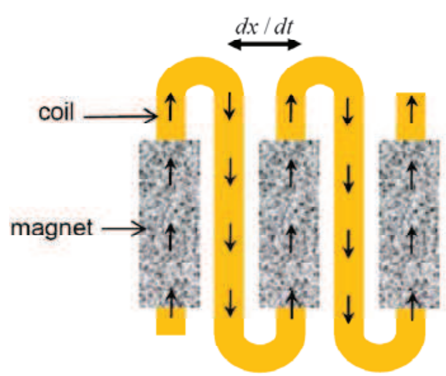

Fig. 2: Top view of magnet/coil arrangement for multi-pole architecture. Arrows represent the flow of current in the coil. Note that the magnets are magnetized in out of plane.

FABRICATION PROCESS

Based on the multi-pole architecture, the device is fabricated using standard MEMS microfabrication techniques, with a bonded-powder process for forming the integrated permanent magnets. The device is formed in two parts, one for the magnet array and the other for the cantilever beam with coil. The magnet array (300 µm pole width and spacing) is fabricated by initially patterning stripe-like features in silicon (100) using photolithography (Fig. 3b), followed by deep reactive ion etching (DRIE) to realize approximately 300-µm deep trenches in silicon (Fig. 3c). To make the magnets, NdFeB magnetic powder (Magnequench) mixture consisting of 50 µm and 15 µm particles are used at 50:50 weight ratios, following the processes in [6]. The two different powders are dried using a desiccator, mixed thoroughly, and then filled into the silicon trenches using doctor blade technique (Fig. 3d). The substrate is then parylene coated to bond the magnetic powder.

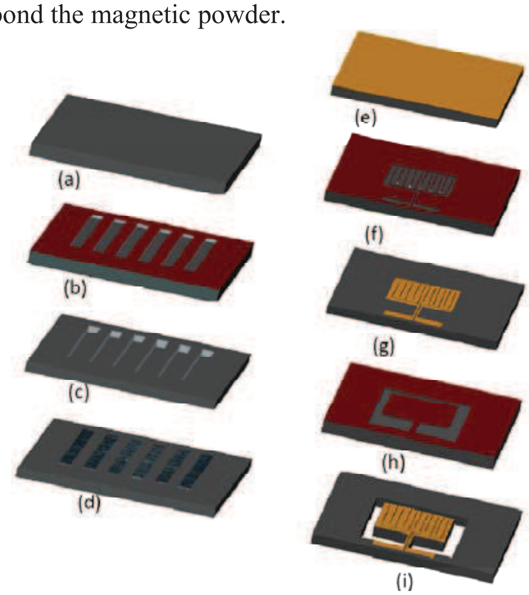

Fig. 3: Fabrication process of the multi-pole electrodynamic energy harvester.

The second part of the device consisting of silicon cantilever beam and copper coil is fabricated as shown in Fig. 3(e-i). A seed layer of Ti/Cu/Ti is deposited on bare silicon (Fig. 3e) and then patterned for electrical coils using standard photolithography (Fig. 3f). After the pattern is realized, the substrate is etched in dilute HF (20 (H_2O):1 (HF)) to remove Ti for subsequent Cu electroplating. Approximately 10-µm-thick Cu is electroplated using a bath of $CuSO_4$ and H_2SO_4 at room temperature at a deposition rate of ~0.2 µm/min. Following electroplating, the photoresist is stripped and a Ti/Cu/Ti etch is performed to remove all the conductive seed layers to have only copper coils (250 µm wide with 50 µm spacing) at the patterned locations (Fig. 3g). The substrate with coils is now re-patterned to form the paddle-like regions and cantilever beam structures (Fig. 3h). Following patterning, a DRIE through-etch is performed to form the released structures (Fig. 3i). The independent magnet and coil structures are then aligned and bonded face-to-face using superglue and a spacer resulting in an air gap of ~100 µm, thus forming the complete energy harvester. The device is then attached to a PCB substrate and the electroplated coil is connected to the lead wires through wirebonding and soldering techniques. The fully fabricated device pictures are shown in Fig. 4.

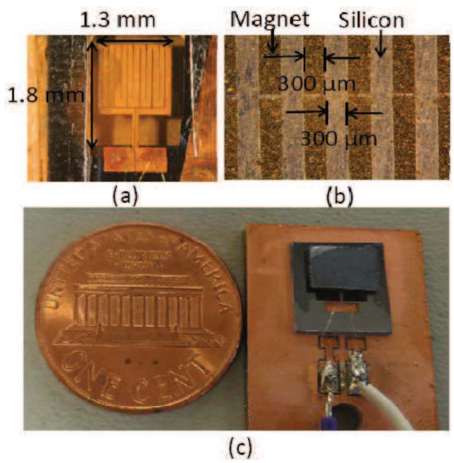

Fig. 4: (a) Silicon cantilever beam with serpentine electroplated copper coil on top, (b) Bonded-powder NdFeB magnets in silicon trenches, (c) Assembled device on a PCB board.

EXPERIMENTAL METHODS

The device is initially characterized to determine the magnetic properties of the bonded magnets and the coil resistance. The magnetic properties of the bonded magnets are evaluated using a vibrating sample magnetometer (VSM). A single magnetic pole (3 mm x 0.3 mm x 0.3 mm) is used as a test sample. The electroplated copper coil resistance is simply measured using a digital multimeter. The coil thickness and silicon cantilever thickness are evaluated from profilometry.

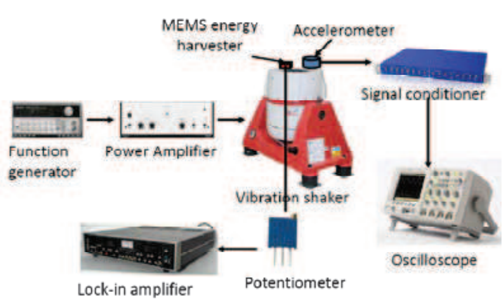

Fig. 5: Experimental setup of the electrodynamic energy harvester.

For energy harvesting testing, the fully bonded device is mounted on a vibration shaker table. A function generator in conjunction with power amplifier is connected to the shaker to provide sinusoidal excitation to the harvester. An accelerometer is also mounted along with the harvester on the shaker to determine the acceleration of sinusoidal vibration via a signal conditioner and oscilloscope. The small output voltage of the energy harvester is measured with a lock-in amplifier. A potentiometer is used to determine the optimal power output of the device. The complete experimental setup is shown in Fig. 5.

RESULTS AND DISCUSSION

The magnetic residual flux density (remanence) and coercivity of the bonded magnets determined from the VSM are 0.56 T and 740 kA/m, respectively. From the obtained residual flux density, a finite element simulation using two magnetic poles of 300 µm x 300 µm separated by 300 µm (as designed in the device process) is performed to determine the average flux density from the magnetic poles in the coil located at 100 µm distance. The average out-of-plane magnetic flux density in the coil at the magnet and no magnet location is found to be +0.08 T (up) and -0.003 T (down), as shown in Fig. 6.

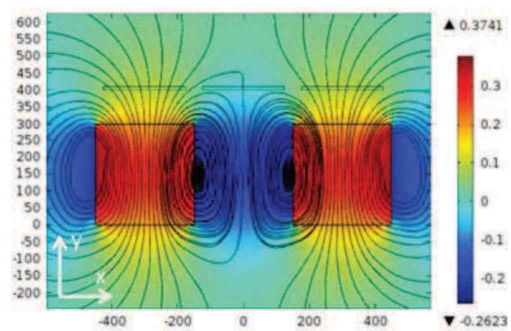

Fig. 6: Simulation of magnetic flux density (B-field) in the y-direction from the magnetic arrays.

The coil resistance is determined to be 0.8 Ω, and the thickness of the coil and the silicon cantilever beam are found to be 10 µm and 580 µm, respectively. The natural frequency of the harvester is determined by sweeping the frequency of the function generator and monitoring the open circuit voltage of the harvester. The peak voltage corresponds to a natural frequency of 5 kHz. To determine the peak power output at resonance, the device is vibrated at its natural frequency, and an external load resistance is swept using the potentiometer and the corresponding power output is recorded, as shown in Fig. 7. A peak power output of 9.3 pW is obtained at 1.5 Ω for 1 g.

Later, the device is tested for linearity with respect to an increase in acceleration. The power output at the optimal load resistance of 1.5 Ω is plotted as a function of excitation frequency for accelerations ranging from 1 g to 4 g, as shown in Fig. 8. Peak load powers of 9.3 pW, 37.5 pW, 96 pW, and 171 pW are obtained at 1 g, 2 g, 3 g, and 4 g accelerations, respectively, at the natural frequency of 5 kHz. These results suggest that the device exhibits good linearity, since the resonant frequency of the beam remained constant for four different input accelerations and the power generation increased quadratically. The harvester mechanical quality factor is also determined to be ~100.

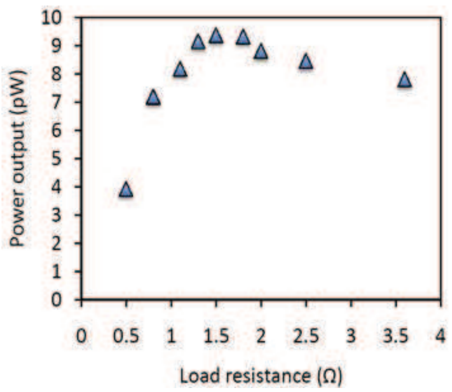

Fig. 7: Power output versus load resistance of the energy harvester at 1 g acceleration.

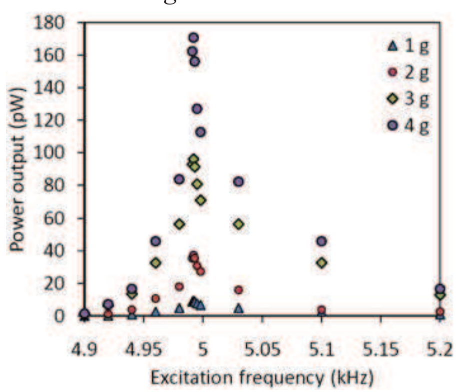

Fig. 8: Power output versus excitation frequency of the energy harvester at 1 g, 2 g, 3 g, and 4 g acceleration.

CONCLUSIONS

In conclusion, an effort has been made to explore the feasibility of developing MEMS scale electrodynamic vibration energy harvester using multi-pole architecture. This basic architecture has the potential to enable larger output voltages and simpler coil layouts compared to single-magnet/single-coil (multi-turn) coil designs. While the demonstrated device outputs load voltages ranging from 3.75 µV to 16 µV (at 1.5 Ω load), the voltage can be increased greatly by increasing the number of magnetic poles. In this work, only 12 magnetic poles (six permanent magnets) are used. In addition, the gap between the coil and the magnetic poles is approximately 100 µm, which when reduced can also significantly improve the output voltage and the corresponding power output. Ongoing work is aimed at further reducing the air gap and exploring devices with finer pole pitch to enable up to 100 poles or more. Other alternatives for better-performing magnetic materials such as sputtered NdFeB magnets are also being explored.

ACKNOWLEDGEMENTS

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