

# MODELING, DESIGN AND FABRICATION OF ( $10 \times 10 \times 4 \text{ MM}^3$ ) MEMS AC ENERGY SCAVENGER FOR SMART GRID APPLICATIONS

Igor Paprotny<sup>1\*</sup>, R.M. White<sup>2</sup>, and P.K. Wright<sup>3</sup>

<sup>1</sup>Department of Electrical Engineering & Computer Sciences, University of California, Berkeley, USA

<sup>2</sup>Berkeley Sensor & Actuator Center (BSAC), Berkeley, USA

<sup>3</sup>Center for Information Technology Research in the Interest of Society (CITRIS), Berkeley, USA

<sup>4</sup>Department of Mechanical Engineering, University of California, Berkeley, USA

\*Presenting Author: igorpapa@eecs.berkeley.edu

**Abstract:** We are developing small and inexpensive self-powered sensor modules that can be non-intrusively deployed throughout the grid to wirelessly monitor current, voltage, as well as other operational and diagnostic parameters. The goal of the MEMS AC scavenger is to provide energy for the module without dominating its footprint. In this paper, we present the design for the scavenger, as well as the results from ongoing modeling and fabrication. At present, the MEMS AC energy scavenger is designed to harvest energy from low ( $I \leq 1 \text{ A}_{\text{RMS}}$ ) current applications, extracting up to  $2 \mu\text{W}$  of power. Our analysis shows that the MEMS AC scavenger should be able to extract tens and perhaps hundreds of  $\mu\text{W}$  from higher currents flowing in a nearby zip-cord.

**Keywords:** Smart Grid, AC energy scavenging, MEMS, Aluminum-Nitride (AlN)

## INTRODUCTION

The upcoming Smart Grid initiative necessitates the distribution of thousands of sensors to monitor the operation of the future U.S. power grid [1]. Our group is using MEMS technologies to develop small and inexpensive self-powered sensor modules that can be non-intrusively deployed (simply attached to equipment) throughout the grid to wirelessly monitor current, voltage, as well as other operational and diagnostic parameters (See Fig. 1, and [2]). The goal of the MEMS AC energy scavenger is to provide energy for operation of on-board sensors, electronics, and low-power radio unit that wirelessly transmits the measured results, without dominating the footprint of the sensor module.

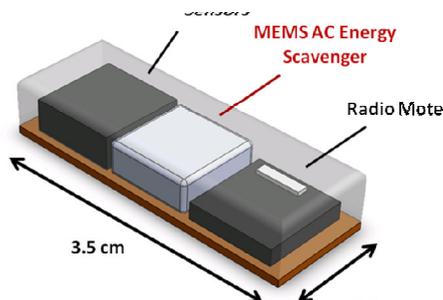


Fig. 1: Conceptual design of our self-powered, wireless MEMS sensor module.

In previous work [3], we have introduced the conceptual design of the MEMS AC energy scavenger, and shown how to optimize its mechanical structure to ensure resonance at power frequencies (60 or 50 Hz) within the limited footprint. In this work we present an

improved design for the MEMS AC scavenger, as well as the results from ongoing modeling and fabrication.

## MEMS AC SCAVENGER DESIGN

We use a quad-folded cantilever design in order to fit the spring within the  $10 \times 10 \times 4 \text{ mm}^3$  volume. To maximize power output, the cantilever structure has to resonate at the electric power frequency (60 Hz in the U.S.). The scavengers are sufficiently large to allow us to combine conventional and microfabrication processes to increase their efficiency. Consequently, we use commercially available NdFeB magnets (K&J Magnetics, Inc.), with a remanent magnetization of  $B_r = 13,700$  Gauss, currently far superior to that of microfabricated magnets [4].

The CAD layout of the MEMS AC energy scavenger is shown in Fig. 2. It consists of a frame (i) and a folded cantilever beam (ii) coated with Aluminum-Nitride (AlN). Both the frame and the spring is monolithically fabricated from either an SOI wafer, or a single-crystal silicon wafer timed-etched to the desired thickness. The magnet (iii) is manually bonded to the spring prior to HF release. Copper ballasts (iv) are attached to the device post-fabrication in order to tune the resonance frequency to precisely match the power frequency.

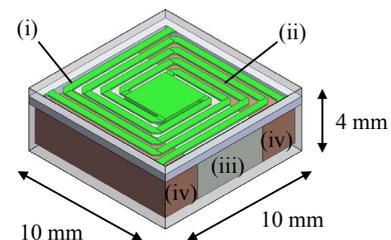


Fig. 2: Design of the MEMS AC Energy Scavenger.

In this paper, we focus on arranging the magnets such that their remanent magnetization vectors provide good coupling with the magnetic field surrounding a typical zip-cord (see Fig. 3.). Other configurations can be used to provide good coupling with a single current-carrying conductor [5].

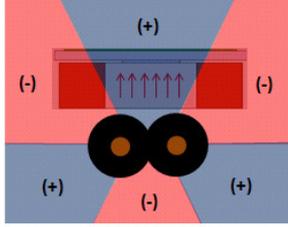


Fig. 3: The size of the magnet is optimized to fit with a single polarity of the magnetic field emanating from the current-carrying zip-cord.

For ease of fabrication, a single layer of AlN is used as the piezoelectric material. The top electrode is lithographically patterned to minimize charge cancellation due to both compressive and tensile stresses present in the piezoelectric layer. The size of the pads has been optimized to maximize power output [6]. The electrode layout is shown in Fig. 4. The stress distribution between the opposite polarity electrodes is asymmetric, and the electrode configuration assumes that both polarities will be connected to separate power conditioning circuits.

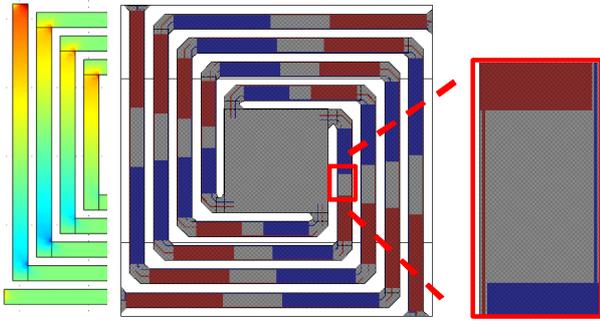


Fig. 4: Electrode layout with alternating electrodes that avoid charge cancellation due to both tensile and compressive stress present in the piezoelectric layer (as shown on the FEM results on the left). The opposite polarity electrode layer is colored red and blue for clarity.

In order to protect the scavenger from over-current conditions, a design that limits the motion of the magnet must be implemented to prevent excessive amplitude of oscillations. We are currently investigating the use of compliant motion limits in the meso-scale AC energy scavengers [5]. We expect similar motion limits to be incorporated in the packaging of the MEMS AC energy scavenger, and are

currently working to incorporate these into our analysis. However, we leave the discussion and modeling of these stoppers for future work.

## MODELING

The MEMS AC scavenger was modeled as a lumped-element single-degree electromechanical system. Due to a symmetric force distribution enacted by the fixed-fixed spring, the rotational inertia of the proof-mass was disregarded. We use formulation from [7] to derive the following representative equations of motion (similar formulation can be found in [8]):

$$m\ddot{x} + kx + b\dot{x} + \alpha q = F_M \quad (1)$$

$$V = \alpha x + \frac{1}{C} q. \quad (2)$$

Eqs. (1) represents the mechanical system, while eq. (2) represents the electrical circuit. In Eqs. (1) and (2),  $m$  is the mass of the magnet,  $k$  is the spring constant,  $x$  is displacement of the magnet,  $b$  is the damping coefficient,  $\alpha$  is the coupling factor,  $C$  is the capacitance of the transducer,  $q$  is the charge, and  $F_M$  is the force on the magnet, calculated using Eq. 3. from [8] (shown below).

$$F_M = B_r \int \frac{d(H_y)}{dy} dV. \quad (3)$$

The force  $F_M$  was calculated numerically using the Finite Element Method (FEM). Fig. 5 shows the gradient of the y-vector of the magnetic field ( $dH_y/dy$ ) within the magnet volume using a current of  $10 A_{RMS}$ . Notice that the field changes sign (direction) near the edges, signifying that the magnet protrudes out of the central (+) region of  $dH_y/dy$  in Fig. 3.

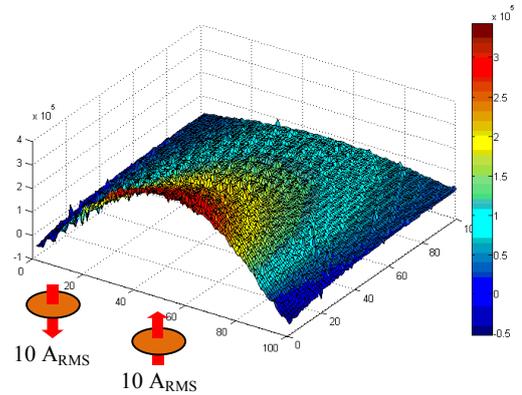


Fig. 5: The gradient of the y-vector of the magnetic field within the volume of the magnet using a current of  $10 A_{RMS}$ . The approximate location of the two conductors of the zip-cord, and the direction of the  $10 A$  currents are indicated. Note that only the magnitude of ( $dH_y/dy$ ) is true scale.

Both the transducer capacitance  $C$ , and the coupling coefficient  $\alpha$  depend on the physical design of the folded beams, as well as the layout of the electrodes. Consequently, both quantities were extracted from a 3D quasi-static electromechanical FEM model. The  $Q$  for our system was conservatively estimated to 70 based on experiments with mesoscale AC energy scavengers.

We modeled the scavenger using the circuit formulations of Eqs. (1) and (2) adopted from [7] in LT-SPICE. The power was dissipated in a simple resistive load  $R_L$ . The circuit representation is shown in Fig. 6.

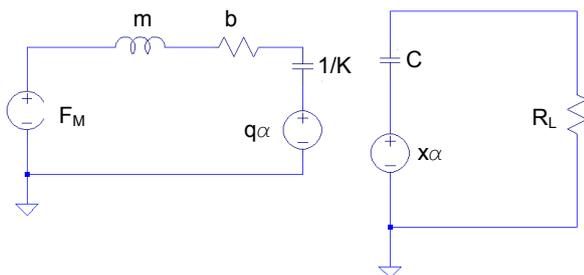


Fig. 6: The circuit diagram formulation of Eqs. (1) and (2). The formulation for our model was adopted from [7].

The time of submission of this paper, the MEMS AC scavenger design was optimized to harvest energy from low-current (up to 1  $A_{RMS}$ ) application. Our analysis indicates that the harvester will be able to output 2  $\mu W$  of power from 1  $A_{RMS}$ . Note that at that 1  $A_{RMS}$  corresponds to a force equivalent to only  $\frac{1}{2}$  G's of acceleration of the proof mass in a conventional vibration energy harvester. The low-powered radio motes we are incorporating in our sensor module require only a few mW of power for operation. Consequently, even 2  $\mu W$  is sufficient to charge a printed capacitor that we envision will be incorporated into the base of the sensor module. This will allow self-powered, albeit low duty cycle, sensing operation.

We are currently in the process of optimizing the designing of the scavenger for higher current operation. In particular, including  $n > 4$  folded cantilever beam segments (optimized according to [4]) will allow us to scavenge reliably from higher currents. Our analysis indicates that we should be able to scavenge on the order of tens of  $\mu W$  from 10  $A_{RMS}$ . Further redesign of the magnetic coupling, as well as optimization of the stress distribution within the piezo-resistive layer could bring the output power perhaps as high as hundreds of  $\mu W$ .

## FABRICATION PROCESS

The AC Energy Scavenger is currently being fabricated in the Berkeley Microlab and Marvel Nanofabrication facility. The process is based on bulk micromachining of an SOI-wafer with 2  $\mu m$  BOX layers. The oxide is used as an etch-stop and release

layer. We are also considering using a timed etch to define the thickness of the spring. The fabrication process is outlined in Fig. 7.

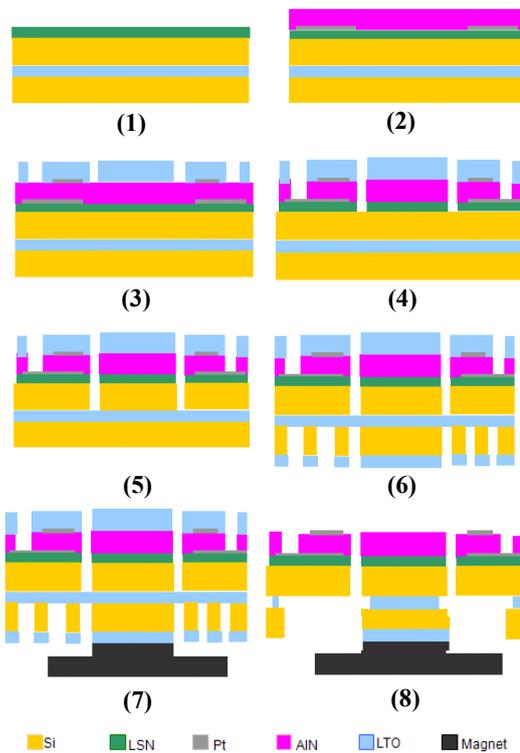


Fig. 7: Outline of the fabrication process for the MEMS AC energy scavenger. Combining mesoscale with microfabrication technologies allows us to combine strong, off-the-shelf NdFeB magnets with lithographically defined spring and electrode structures.

We start by depositing a layer of low-stress SiN on the wafer, which is used as both electrical isolation and etch-stop layers (step 1). Next, we deposit and pattern the bottom electrode layer using lift-off of 100 nm evaporated Ti/Pt. A 1 – 2  $\mu m$  thick layer of AlN nitride is then sputtered onto of the electrodes (step 2). A second (top) layer of electrodes is deposited and patterned using lift-off. An LTO hard mask is deposited and patterned on top of the AlN and electrode layer (step 3). The AlN and SiN are then etched (step 4). The device layer is then etched (DRIE) using the BOX layer as an etch stop (step 5). The wafer is then etched (DRIE) from the back side to provide etch release holes for thinning the springs to achieve the desired thickness (step 6). The same etch is used to separate the individual die. The magnet is then bonded onto the central pedestal using epoxy (step 7). Finally the structure is released in HF (step 8).

## CONCLUSIONS

We presented the design, modeling and fabrication process for a MEMS AC energy scavenger, which is intended to provide power the self-powered wireless

MEMS sensor modules that we are developing to support future Smart Grid infrastructure. Our design combines MEMS and meso-scale fabrication technologies to contain the footprint of our design within a  $10 \times 10 \times 4 \text{ mm}^3$  volume, on the order of an integrated circuit. Due to both compressive and tensile stresses presented in the AlN layer, the electrodes are lithographically patterned to avoid charge cancelation.

The present quad-beam design is optimized for scavenging from low-current ( $I \leq 1 \text{ A}_{\text{RMS}}$ ) applications. Under such a low current, our device should be able to output approximately  $2 \mu\text{W}$  of power; an output that is comparable to other AlN-based energy scavenger. Our analysis indicates alternate designs that will allow us to scavenge tens, and maybe as much as hundreds of  $\mu\text{W}$  from a zip-cord carrying tens of  $\text{A}_{\text{RMS}}$ .

We also outlined a fabrication process that is based on bulk micromachining of SOI wafers. The fabrication of the AC energy scavenger is currently ongoing in the Berkeley Microlab and Marvel Nanofabrication facility. We look forward to validating the modeling analysis with actual experimental results, and to report these as they become available.

#### ACKNOWLEDGEMENTS

The authors would like to thank Professor Einar Halvorsen, Duy Son Nguyen, and Dr Eli Leland and for their help with this project. This work was supported by grants from the California Energy Commission (CEC), contract numbers 500-01-43, 500-02-004 and POB219-B, as well as research and infrastructural grants from the Berkeley Sensor & Actuator Center (BSAC) and the Center for Information Technology Research in the Interest of Society (CITRIS), at the University of California, Berkeley.

This report was prepared as a result of work sponsored by the California Energy Commission. It does not necessarily represent the views of the Energy Commission, its employees, or the State of California. The Energy Commission, the State of California, its employees, contractors, and subcontractors make no warranty, express or implied, and assume no legal liability for the information in this report; nor does any party represent that the use of this information will not infringe upon privately owned rights.

#### REFERENCES

- [1] NIST Framework and Roadmap for Smart Grid Interoperability Standards, Rel. 1, National Institute for Standards and Technology (NIST), USA, January 2010.
- [2] Paprotny I., E. Leland, C. Sherman, R.M. White and P.K. Wright, Self-powered MEMS Sensor Module for Measuring Electrical Quantities in Residential, Commercial, Distribution and Transmission Power Systems. *in Proc. ECCE 2010*, Sep. 13 – 16 2010.
- [3] Paprotny I., E. Leland, and R.M. White, Optimization of a Die-sized ( $10 \times 10 \times 4 \text{ mm}^3$ ) MEMS AC Energy Scavenger for Residential and Commercial Electricity End-use Monitoring. *in Proc. PowerMEMS 2009*, Dec. 1-4 2009.
- [4] Bowers B, Agashe J, Arnold DP 2007 A method to form bonded micromagnets embedded in silicon, *14th Int. Conf. Solid-State Sens., Actuators, Microsyst. Tech. Dig.*, Jun. 2007, 2 1581-1584.
- [5] Xu Q., R.M. White, I. Paprotny, and P.K. Wright. Improved Performance of Nonlinear Piezoelectric AC Energy Scavengers. to appear in *Proc. PowerMEMS 2010*, Nov. 30 – Dec. 3 2010.
- [6] Nguen D.S., I. Paprotny, R.M. White, and E. Halvorsen, unpublished.
- [7] Blystad L-C.J., E. Halvorsen, and S. Husa, Piezoelectric MEMS Energy Harvesting Systems Driven by Harmonic and Random Vibrations. *IEEE Trans. Ultr. Ferrel. Freq. Cont.*, 57 (4), Apr. 2010, 908-919.
- [8] Wagner B., M. Kreutzer, and W. Becker, Permanent Magnet Micromotors on Silicon Substrates. *J. MEMS*, 2 (1), Mar. 1993, 23-29.