

OPTIMIZATION OF A DIE-SIZED (10X10X4 MM³) MEMS AC ENERGY SCAVENGER FOR RESIDENTIAL AND COMMERCIAL ELECTRICITY END-USE MONITORING

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Abstract: We present the optimization, design and fabrication of a proximity MEMS AC energy scavenger that fits within a 10x10x4 mm³ volume, the typical size of a microfabricated integrated circuit. This size limitation was chosen so that our scavenger can seamlessly be integrated into a printed circuit board without dominating the board's footprint. Such a small form-factor will enable the fabrication of small self-contained wireless sensor nodes that incorporate the die-sized AC energy scavenger, a MEMS current sensor, as well as wireless radio chip, for providing sub-metering at the individual appliance level in residential and commercial settings.

Keywords: Energy Scavenging, Power cords, MEMS, Magnetic, Piezoelectric Transduction, Die-sized

INTRODUCTION

Ongoing initiatives for energy conservation dictate the need for ubiquitous sensing of electrical power use in residential and commercial settings. One such example is the Demand Response (DR) initiative [1], where a variable pricing structure is used to curb demand during peak hours. In this paper we present the optimization, design and fabrication of a proximity MEMS AC energy scavenger that fits within a 10x10x4 mm³ volume, the size of a typical microfabricated integrated circuit. This size limitation was chosen so that the device can be seamlessly incorporated into a printed circuit board without dominating the board's footprint. This small form-factor will allow the design of small self-contained wireless sensor nodes that incorporate the die-sized scavenger, a MEMS current sensor [2], a wireless radio chip, and a power storage unit (rechargeable battery or capacitor) within a package roughly the size of a memory stick (Fig. 1).

The scavenger is based on the transduction of mechanical force acting upon a permanent magnet by an alternating magnetic field from a current-carrying two-wire appliance *zip-cord*. As shown in Fig. 2, the y-gradient of the magnetic field generated around a zip-cord creates a local maximum in the middle between the two conductors. To maximize the force, the magnet must be magnetized in the direction of the y-field gradient, and placed in the middle above these conductors. If the magnet is attached to the end of a cantilever beam, the generated force will cause oscillating deflection of the beam. If a portion of the beam is covered with a piezoelectric material,

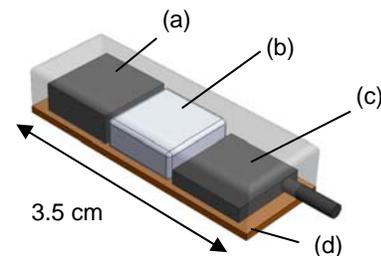


Fig. 1: The proposed memory-stick sized wireless sensor node containing the die-sized current scavenger (a), a MEMS current sensor circuit (b), and a wireless radio chip (c). Printed energy storage (battery or capacitor) can be incorporated within the printed circuit board substrate (d).

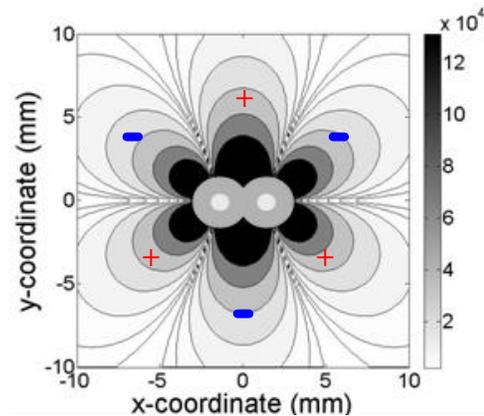


Fig. 2: The magnitude of the y-component of the magnetic field gradient around a zip-cord. Regions of opposing polarity of the H-field are marked with + and - signs, respectively.

the resulting periodic deflection can be used to generate electric power. This principle, illustrated in Fig. 3, has been tested successfully using large-scale devices [3]. However, the size of these devices does not readily allow integration into distributed sensor-nodes due to their large footprint requirements. The purpose of this work is to reduce the size of the scavenger to that of a microfabricated integrated circuit ($10 \times 10 \times 4 \text{ mm}^3$), while optimizing its design to maximize the power output.

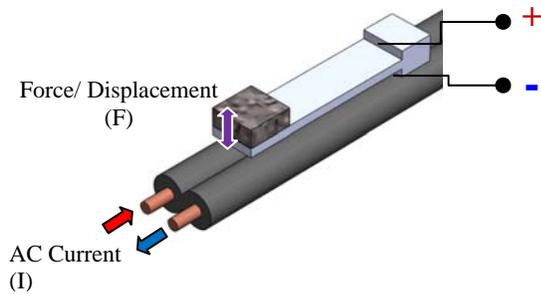


Fig. 3: The principle of the AC energy scavenger. A cantilever beam with a magnet on its tip is placed on top of a current-carrying zip-cord. If the beam is coated with piezoelectric material, the oscillating stress and strain will cause it to deliver electric power.

The idea of scavenging power from energized cables using electromechanical transduction from the alternating magnetic field was initially proposed here [3]. Although electromagnetic approaches that enclose the wire, such as clamp-on current transformers or Rogowski coils, can conceivably be used to scavenge energy from single-wire current-carrying conductors, they cannot be applied to zip-cords due to opposing magnetic fields of the individual conductors.

DESIGN CONSIDERATIONS

We chose a quad-folded cantilever design in order to fit the cantilever of the beam 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. 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].

We extended the microfabrication process from [2] to allow for reliable fabrication of thin beam

structures. The new process allows us to fabricate a folded beam structure that maximizes the area covered by the piezoelectric material. Due to ease of deposition, we chose a $1 \mu\text{m}$ thick layer of aluminum nitride (AlN) as the piezoelectric material.

The basic design of the scavenger with the relevant design parameters is presented in Figs. 4 and 5, while the flexible design parameters, over which the scavenger is optimized, are listed in Table 1. The magnet (A) is bonded onto a spacer (B), which in turn is bonded to the base of the quad-folded spring assembly (C) (a magnet can also be used as a spacer to further increase power output and decrease the resonant frequency). In order to ensure adequate bonding, the size of the base was set at $3 \times 3 \text{ mm}^2$. The magnet is suspended below the spring assembly to increase its stability due to gravitational pull on the magnet. A 0.5 mm wide rim (D) surrounds the folded spring assembly to ensure stability. The spring assembly is fabricated from a $\sim 400 \mu\text{m}$ thick SOI silicon wafer with a $100 \mu\text{m}$ device layer. The leaves of the folded spring are thinned to $100 \mu\text{m}$ using the buried oxide as the etch stop, and release layer.

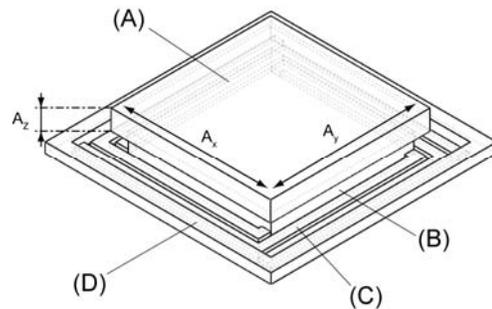


Fig. 4: Design of the energy scavenger (orthogonal view).

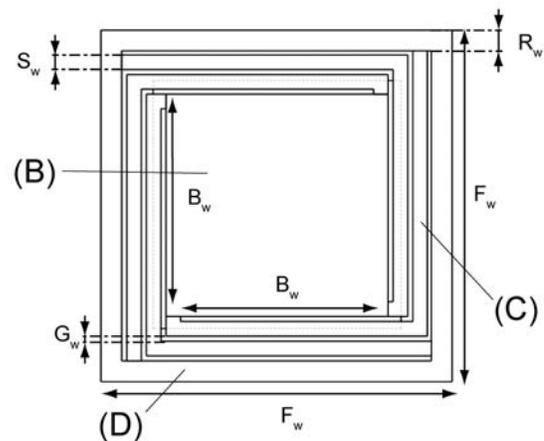


Fig. 5: Design of the energy scavenger (top view).

Table 1: The design space.

S_w	the width of folded spring
G_w	the width of the gap
n	number of turns of folded spring
A_y	side of the magnet (y)
A_x	side of the magnet (x)
A_z	height of magnet top

DESIGN OPTIMIZATION

The current scavenger is large enough to allow bonding of commercially available NdFeB magnets (www.kjmagnetics.com). The A_x and A_z parameters were chosen among discretely available for off-the-shelf magnets to maximize the volume within the die-size limitation (including deflection due to gravitation). The A_y parameter was chosen such that the magnet fits completely within a single region of polarity of the H-field gradient (+ on Fig. 2) on the center of the zip-cord. To maximize A_z , two magnets with coincidental B_r fields are stacked on top of each other, yielding a magnet with dimensions $A_x=9.53$ mm, $A_y=4.76$ mm, and $A_z=2.38$ mm. The total mass of both magnets is 810 mg.

In order to maximize the power output of the current scavenger, the folded spring was designed to maximize the area covered by the beams while maintaining a 60 Hz resonant frequency. Given the width of the gap between the beams in the folded spring (G_w), the length of each i^{th} spring member (L_i) and its width (S_w) can be described using the following equations:

$$x_s = F_x - B_w - 2G_w \quad (1)$$

$$L_i = x_s - i(S_w + G_w) - (i-1)S_w - (i-2)G_w \quad (2)$$

$$S = \frac{F_w - 2R_w - B_w - 4G_w}{2} \quad (3)$$

$$S_w = \frac{S - (n-1)G_w}{n}, \quad (4)$$

where B_w is the width of the base and R_w is the width of the frame (see Figs. 4 and 5). Eqs. (1) - (4) assume uniform width of the individual spring members. Based on our desire to reduce the risk of beam-to-beam contact while maximizing the area covered by AlN, G_w was chosen to be between 100 μm and 250 μm . Fig. 6 shows the folded spring assembly for $n = 1, 2, 3$ and 4, while the corresponding values of S_w are shown in Table 2.

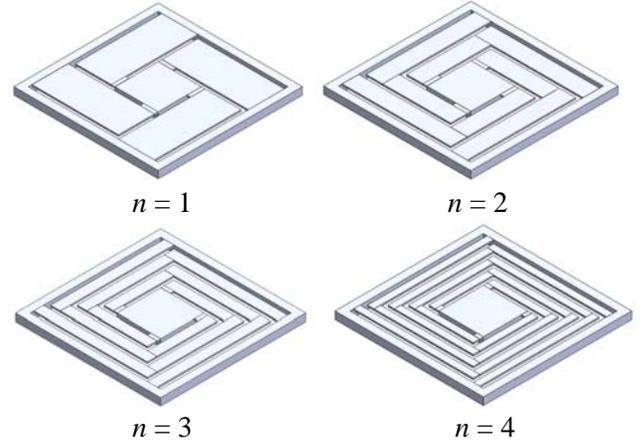


Fig. 6: The quad-folded spring assemblies for $n = 1, 2, 3$, and 4, with $G_w=250 \mu\text{m}$.

Table 2: The values of S_w for $n = 1, 2, 3$, and 4, with $G_w=250 \mu\text{m}$.

n	1	2	3	4
S_w [mm]	2.5	1.125	0.667	0.437

Finite element analysis (FEA) was used to obtain the spring-constants for each n value. The resonant frequency (f_r) of the energy scavenger was calculated for the four spring assemblies, as shown in Fig. 7, for both $G_w = 100 \mu\text{m}$ and $G_w = 250 \mu\text{m}$. The scavenger design that uses the $n=4$ folded spring assembly spans the 60 Hz resonant frequency range, and was thus chosen for fabrication.

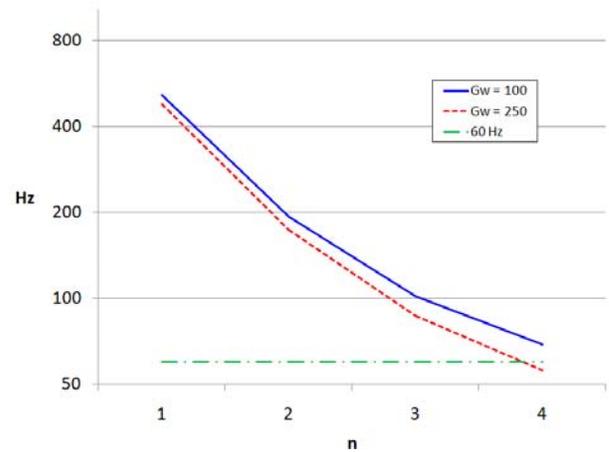


Fig. 7: Plot of the resonant frequency, f_r , for the energy scavenger with $n = 1, 2, 3$ and 4 folded spring assembly. Data for both $G_w=100 \mu\text{m}$ and $G_w=250 \mu\text{m}$ are presented. The green line represents 60 Hz.

Note that f_r for the $n = 4$ system can be further lowered to below 50 Hz by adding additional non-magnetic material, such as copper to the sides of the magnet. In fact, post-fabrication addition of such mass will allow us to *tune* the resonant frequency of the scavenger to 60 Hz.

THE FABRICATION PROCESS

We have developed a fabrication process that will allow us to manufacture our energy scavenger entirely in the Berkeley Microfabrication facility. We use a $\sim 400 \mu\text{m}$ handle wafer with a $100 \mu\text{m}$ device layer to ensure uniform and reproducible thinning of the wafer structure for $100 \mu\text{m}$ thick spring beams. The six steps of the process are outlined in Fig. 8. We anticipate that the magnet and spacer will be bonded post-release; however we will investigate the possibility of pre-release bonding (essentially swapping steps 5 and 6).

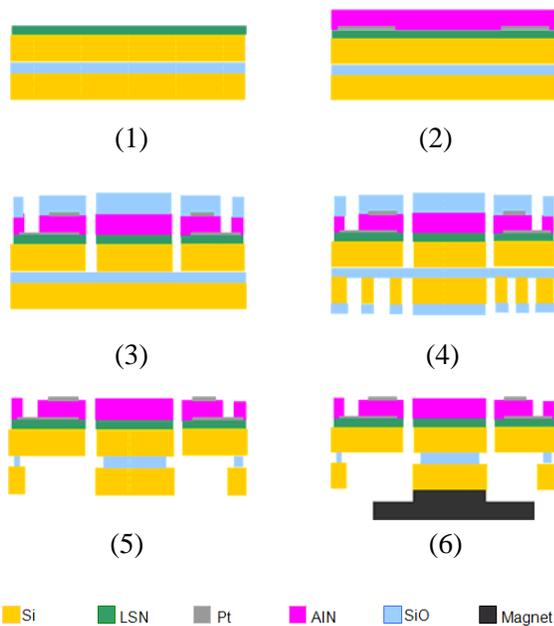


Fig. 8: Summary of the six-step fabrication process.

The geometry of the piezoelectric layer and the top electrodes is determined by the “polarity” of the stress distribution on the beams in the folded spring. This distribution is obtained through FEM analysis. An example of the stress distribution obtained from the FEA model of the $n = 4$, $G_w = 200 \mu\text{m}$ spring assembly is shown in Fig. 9.

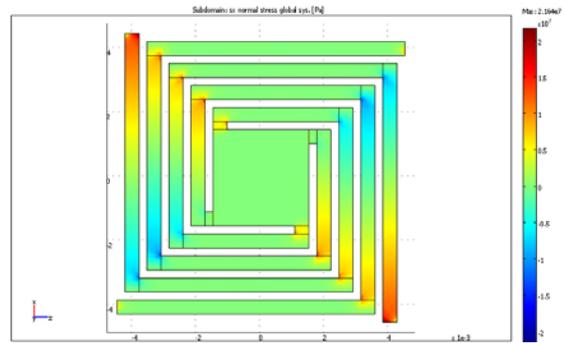


Fig. 9: FEA results showing the stress distribution in the length (x) direction of the beams (left and right side only). Symmetry ensures that an identical stress distribution exists in the upper and lower beams, in the direction of the z -axis.

CONCLUSION

We have shown the optimization of the mechanical design for a die-sized AC energy scavenger. We believe the $10 \times 10 \times 4 \text{ mm}^3$ form factor will allow our device to be seamlessly integrated into wireless current sensor nodes, which can be placed on zip-cords in residential settings for sub-metering purposes. Our method for optimizing the design presented in this paper can easily be adapted to other form factors or different processing constraints.

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