STACKED ELECTRET ENERGY HARVESTING SYSTEM FABRICATED WITH FOLDED FLEXIBLE PRINTED CIRCUIT BOARD

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Abstract: Electret energy harvesters are one of the most promising energy scavenging devices since it is self-sustained and can easily be integrated with IC or MEMS processes. Several out-of-plane electret energy harvesters have been previously demonstrated. The major disadvantages of the previous designs are their large area and thus low area power density. This paper presents an out-of-plane electret energy harvesting system composed of multiple stacked harvesters to reduce the footprint while increasing the output power. Flexible printed circuit boards (FPCB) were used for both electrical wiring and mechanical structures such as springs and supports. An energy harvesting IC was utilized to regulate the output power and more than 2 μW power bursts were obtained at 4-g vibration.

Keywords: electret, energy harvesting, vibration, flexible printed circuit, power management

INTRODUCTION

Energy harvesting has gained much attention in recent years due to its applicability on wireless sensor networks, structural health monitoring and portable power supplies. Due to the continuous advance of the integrated circuit and microsystem technology, it is becoming possible to replace batteries as the power source of low power electronics by scavenging ambient energy such as heat, light and vibration [1]. Research on the vibration-based energy harvesting has been steadily increasing in the past years [2-5]. Electrostatic energy harvesting has the advantage of MEMS/IC process compatibility, giving it the edge over other solutions. A bias source is needed to charge the variable capacitors in the electrostatic energy harvesters to enable the energy conversion cycles. Common biasing sources of electrostatic energy harvesters include batteries, initially charged capacitors, work function difference between two metals, and electrets. Electret has the advantage of self-sustainability, good charge stability, and large power density. Therefore, electret-based harvesters have been the focus of many recent research works [4-6].

In our previous study, a low-cost out-of-plane electret energy harvester was developed by using copper plates as springs and masses [6]. The measured power output was 20.7 μW at 110 Hz for a 2-g vibration input at an effective area of 4 cm^2. The major disadvantage of the previous design was the large area and thus low areal power density. In this study, we present a novel folded design to minimize the footprint of the energy harvesters by stacking 3 out-of-plane unit harvesters and develop an energy harvesting system by integrating the electret generators with a power management IC, all fabricated and incorporated in one custom designed flexible printed circuit board (FPCB). The output characteristics were measured and compared to circuit simulation.

PRINCIPLE AND ANALYSIS

As shown in Fig. 1, out-of-plane electret harvesters are made by placing electret materials and proof masses on the folded FPCB. One unit harvester is composed of two electrodes; one holds the electret and the other, a counter electrode, is placed in parallel with the electret electrode. Together they form a variable capacitor. Current flows though the external load resistor whenever the capacitance changes due to the vibration-driven electrode displacement.

The FPCB is shown in Fig. 2. The charged SiO_2/SiN electrets on Si substrates are placed and bonded on the electret electrodes (Fig. 2(b)). When the FPCB is folded, electret and counter electrodes will face each other to form the two electrodes of the harvester. For the FPCB shown in Fig. 2, three unit harvesters can be stacked. The FPCB is configured in such a way that it would electrically connect the unit harvesters in parallel.

In Fig. 1, the harvesters are designed such that a set of layers would resonate at low frequency and the other set of layers at higher frequency. This is done by following the equation of the spring constant of a fixed-guided beam,

$$k = Ewt^3 / \ell^3, \quad (1)$$

wherein *E, w, t* and *ℓ* are the effective Young's modulus, width, thickness and length of the beam, respectively. By the adjusting the width in Eq. (1) and the mass of the proof mass, the resonant frequency of the electrodes can be changed through the equation $\omega_n = \sqrt{k/m}$. Thus, layers 2, 4 and 6 in Fig. 1 are set to a low resonance by connecting them to 4 thin FPCB's as shown on Fig 2(b). Layers 1, 3 and 5 are connected to 2 wide FPCB's and have much higher resonance frequency, as shown in Fig. 2(c). When the device is excited by a vibration at the low resonance frequency, the low-frequency electrodes have large displacement while the high-frequency electrodes remain relatively still. The large relative displacement causes a significant change in capacitance and induces charge variation on the electrodes and an AC current through the external resistor. Connecting multiple unit harvesters can increase output current and power. The unit harvester pair formed by layers 3 and 4 is purposefully inverted so that all unit harvesters have the same current polarity.

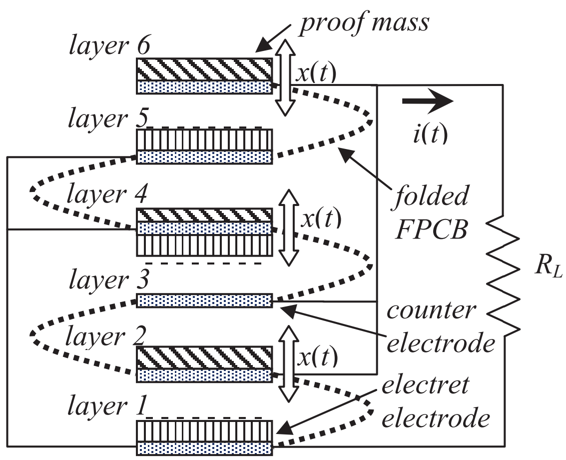

Figure 1. Folded and stacked out-of-plane electret energy harvesters.

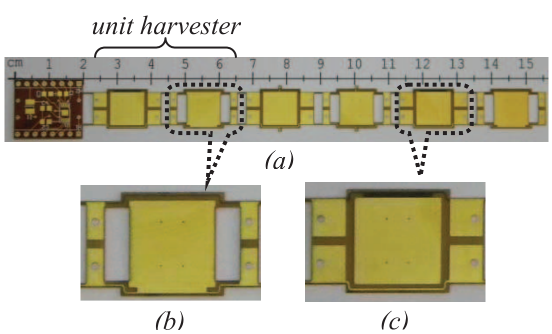

Figure 2. (a) FPCB for device assembly, (b) electret-electrode with low resonance frequency, (c) counter electrode with high resonance frequency.

FABRICATION

The electrets were SiO_2/SiN double layers fabricated by depositing 1-μm-thick SiO_2 and 50-nm-thick SiN via PECVD on a 525-μm thick silicon wafer. The wafer was sliced into 1-cm^2 dices and corona charged to obtain a 350-V surface potential [6]. The assembly of the device (Fig. 3) started by attaching poles on a rigid PCB that served as the holder of the FPCB (Fig. 3(a)). Proof masses and charged electrets were attached on the FPCB by using silver paint. The FPCB was then folded and inserted into the poles on the holder to form the energy harvesting stack (Fig. 3(b)). Plastic strips with dimension of 1mm×10cm×730μm were used as spacers to maintain a gap of 200 μm between the surfaces of the electrets and the counter electrodes. After all the layers were in place, another rigid PCB along with the power management circuits was placed on top to hold the FPCB firmly (Fig. 3(c)). Fig. 4 shows the 2cm×2cm×1.5cm prototype of the assembled electret energy harvesting system.

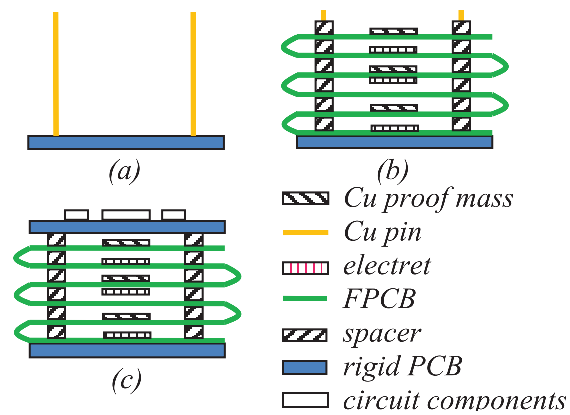

Figure 3. Fabrication and assembly process.

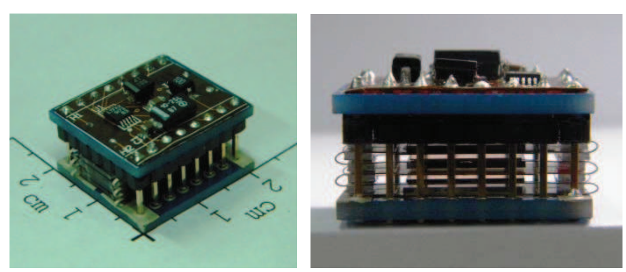

Figure 4. Assembled energy harvesting system.

POWER GENERATION EXPERIMENT

Fig. 5 shows the setup of the power generation experiments by using an electromagnetic shaker. The harvester was initially tested without the power management circuitry (Fig. 1). The output voltage was measured from a small resistor of 1MΩ in series with the load resistor. Fig. 6 shows the output power for various vibration frequency. Multiple peaks in the frequency response indicate mismatched unit harvesters. Maximum output power was found to be at the frequency of 156 Hz. Fig. 7 is the output voltage waveform and Fig. 8 is the output power for various test conditions. Without the power management circuit, the maximum output power at 4-g acceleration was 33.1 µW on a 20-MΩ load at 156 Hz.

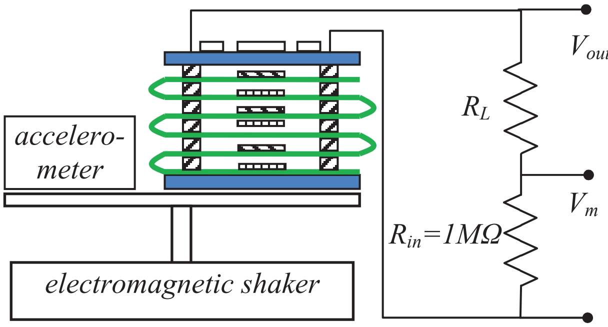

Figure 5. Power generation measurement setup.

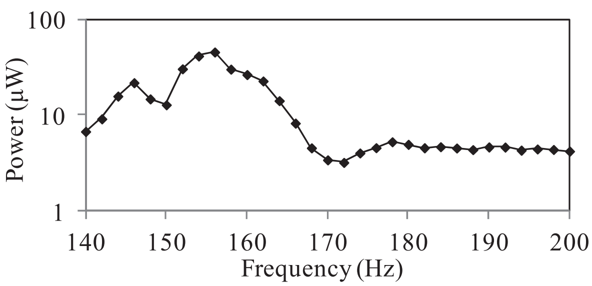

Figure 6. Frequency response on a 20-MΩ load at 4-g acceleration.

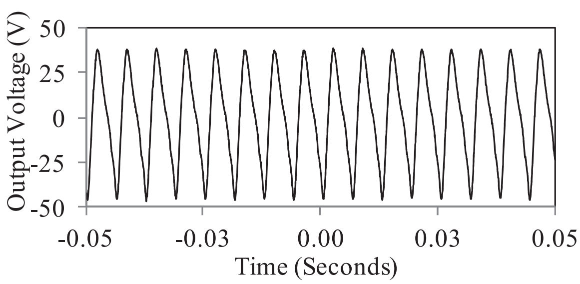

Figure 7. Output voltage on a 20-MΩ load at 4-g acceleration at 156Hz.

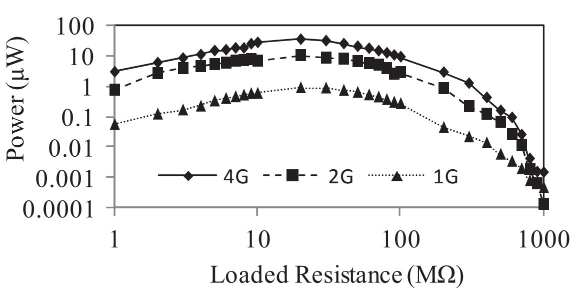

Figure 8. Output power at 156Hz.

ENERGY HARVESTING SYSTEM

The prototype of an energy harvesting system was developed by connecting the stacked harvesters to a LTC3588-1 power management IC from Linear Technology [7]. Fig. 9 shows the circuit model.

The behavior of the harvesting system was simulated by using LTSpice. A simple circuit model of the electret energy harvesters is composed of a voltage source V_H at 156 Hz and a series capacitance C_i representing the initial capacitance between the electrodes and the charge layer in the electret. Another capacitance C_p was used as the total parasitic capacitance at the output node of the harvesters. The energy harvesting system works by storing the energy produced by the harvesters in the storage capacitor C_{store} until it reaches the minimum level required to output a regulated voltage of 1.8 V. With proper choice of V_H and C_p as the fitting parameters, the simulation shows that the system could deliver a regulated voltage burst V_{out} of 1.8 V within 91 seconds of startup on a 1.5-kΩ load for 19-ms duration (Figs. 10 and 11). An interval of 32-s is maintained for every succeeding voltage burst.

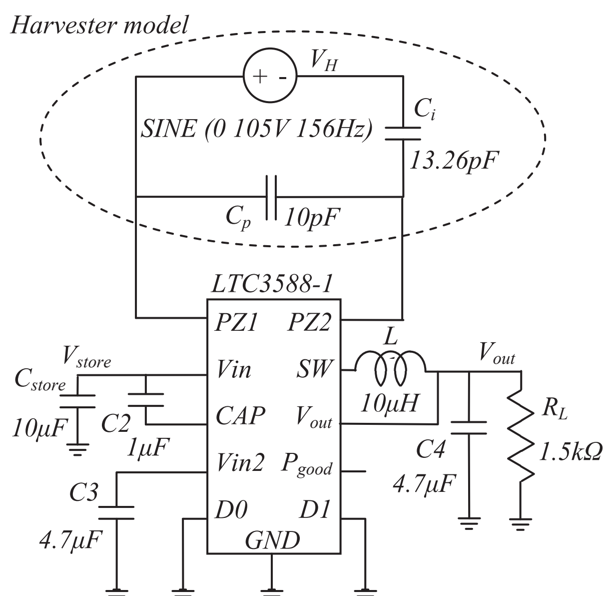

Figure 9. Energy harvesting system prototype.

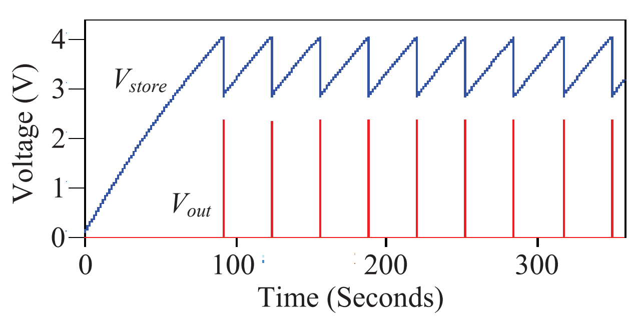

Figure 10. Simulated V_{store} and V_{out}.

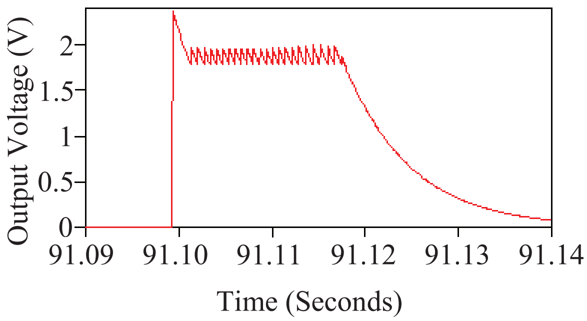

Figure 11. Simulated V_{out} output burst.

Figs. 12 and 13 show the measured time traces of the voltage V_{store} on the storage capacitor C_{store} and the voltage V_{out} across the loading resistor R_L. The system started by storing the energy in C_{store} until it reaches 3.7 V. It took 255 seconds before starting delivering a regulated voltage of 1.8 V for 15 ms on the 1.5-kΩ resistor. The system maintained 32-s intervals for every succeeding voltage burst. Whereas the simulated and measured voltages show good qualitative agreement, the modeling of the voltage source V_H and the parasitic capacitance C_p are in process in order to further verify the behavior of the harvesters.

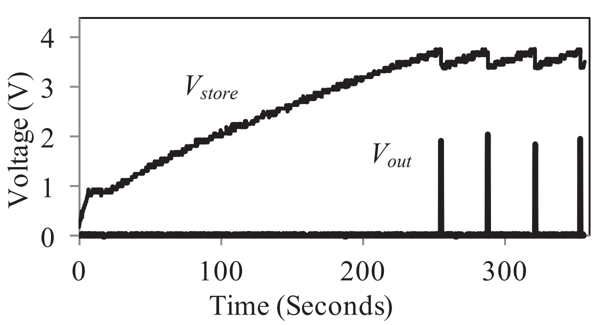

Figure 12. Measured V_{store} on the storage capacitor and V_{out} at the output terminal of the power management IC at 4-g acceleration at 156 Hz.

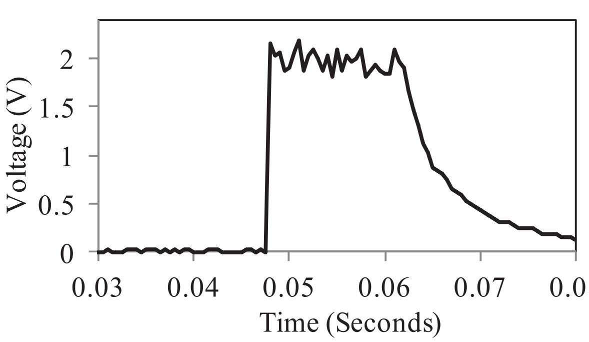

Figure 13. Measured V_{out} output burst.

CONCLUSION

This paper presents an approach on decreasing the footprint of electret energy harvesters by stacking several unit harvesters on a custom designed FPCB. Without power management circuitry, the maximum output power at 4-g acceleration was 33.1 μW on a 20-MΩ load at 156 Hz. Upon connecting the LTC3588-1 power management IC from Linear Technology, the system could deliver a regulated voltage burst of 1.8 V within 255 seconds of startup on a 1.5-kΩ load for 15-ms duration. Moreover, the system maintained 32-s intervals for every succeeding voltage burst.

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