Electrostatic MEMS vibration energy harvester for HVAC applications

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Abstract. This paper reports on an electrostatic MEMS vibration energy harvester with gap-closing interdigitated electrodes, designed for and tested on HVAC air ducts. The device is fabricated on SOI wafers using a custom microfabrication process. A dual-level physical stopper system is implemented in order to control the minimum gap between the electrodes and maximize the power output. It utilizes cantilever beams to absorb a portion of the impact energy as the electrodes approach the impact point, and a film of parylene with nanometer thickness deposited on the electrode sidewalls, which defines the absolute minimum gap and provides electrical insulation. The fabricated device was first tested on a vibration shaker to characterize its resonant behavior. The device exhibits spring hardening behavior due to impacts with the stoppers and spring softening behavior with increasing voltage bias. Testing was carried out on HVAC air duct vibrating with an RMS acceleration of 155 mg and a primary frequency of 60 Hz with a PSD of $7.15 \times 10^{-2}$ g²/Hz. The peak power measured is 12nW (0.6 nW RMS) with a PSD of $6.9 \times 10^{-11}$ W/Hz at 240 Hz (four times of the primary frequency of 60 Hz), which is the highest output reported for similar vibration conditions and biasing voltages.

1. Introduction

Improving energy efficiency of buildings is of critical importance as power consumption has increased significantly in both private and public building sectors [1]. Building energy usage makes up 40% of the US energy consumption and is one of the largest worldwide polluters; for instance in 2005 U.S. buildings contributed 9% of the world's carbon dioxide emissions, ranking third worldwide as a source of carbon emission [2]. To address this, an increasing level of research effort is being dedicated to developing building automation systems (BAS) to better manage energy expenditures. Developing autonomous energy sources to power wireless sensors of BAS is another facet of this effort, as batteries are perceived as nuisance and added maintenance cost by potential BAS users due to their relatively short lifetime. In this context, this paper investigates vibration electrostatic MEMS vibration energy harvesters designed to work on HVAC ducts in a large building.

Vibrations are of particular interest for energy harvesting as they are ubiquitous in buildings, especially in HVAC systems which have air ducts that span the building interior, and they have ample potential for harvesting. The MEMS harvester designed here uses interdigitated electrodes with a gap closing configuration to form a variable capacitor. The energy harvested with such structure depends
on the difference between and ratio of maximum and minimum capacitance, as well as frequency of vibration and applied bias. While the minimum capacitance is when the mobile electrode is equally distanced from each fixed electrode that is set by initial device geometry, maximum capacitance is controlled here by displacement limiting physical stoppers. The physical stopper consists of two different stopping mechanisms that act in conjunction: first, when approaching the fixed electrode, the moving electrode makes contact with cantilever beams connected to the non-moving portion of the device that absorb a portion of the impact energy (figure 1). However, the electrode continues to move in the same direction, albeit decelerating. Next the final contact is with a film of parylene-C with nanometer thickness deposited on the electrode sidewalls, which defines the absolute minimum gap and also provides electrical insulation (figure 1). The thin film stopper can provide much smaller electrode separation gap as compared to microfabricated physical stoppers which are defined by lithography and etching, a process that limit the resolution (and minimum gap) to 1 µm or larger [3–6]. Thus, the power output in the presence of the dual-level stopper is expected to increase significantly. The devices are fabricated with silicon-on-insulator (SOI) wafers using a custom microfabrication process. They are tested first on a shaker table to characterize the dynamic response, followed by performance characterization when mounted on HVAC ducts in the laboratory.

![Figure 1](https://example.com/figure1.png)

**Figure 1.** Dual-level stopper system in a gap closing electrostatic harvester.

### 2. Vibration study

Before discussing harvester design, fabrication, and testing, a few design considerations are presented first. As mentioned above, the devices investigated here are intended to work on HVAC systems. Thus, a thorough vibration study was conducted on the HVAC duct work in the authors’ laboratory in order to understand the frequency spectrum available. An Analog Devices ADXL335 3-axis accelerometer was mounted to a 1 inch square stainless steel plate and magnetically attached to 16 different locations on the air ducts. In regard to the orientation of the accelerometer with the air duct, the z-axis is always normal to the duct wall, the y-axis parallel to the air flow direction, and x-axis perpendicular to the flow direction.

The vibration data was analyzed using the power spectral density function (PSD) to find the frequency and power content of the vibrations. The Signal Processing Toolbox of Matlab contains several PSD estimate functions and the *pmtm* function was chosen in this analysis for its high quality estimation. The results of the PSD for all axis and locations tested are shown in figure 2. All together the most prominent frequencies were 45, 60, 65, and 120 Hz. The axis normal to the duct wall (z-axis) contained the highest amplitude of vibrations by two orders of magnitude. The average PSD amplitude at these peaks is on the order of $10^{-4}$ g²/Hz. This amplitude is on the lower end of what others have reported measurements of [7] or driven devices with [4,6,8]. Based on these results, the devices were design to resonate at 65 Hz. Spring softening from electrostatic forces and spring hardening from stopper impacts will broaden the resonant bandwidth to where acceleration PSD is greatest (45-120 Hz).
3. Design and fabrication

The device was fabricated on SOI wafer with 200 µm device layer and 350 µm handle layer using a custom microfabrication process developed at Cornell Nanoscale Science and Technology Facility (CNF). As mentioned above, it is designed to resonate 65 Hz frequency range, where the maximal amount of vibration power is available in the HVAC ducts. Gap-closing interdigitated electrodes with 22 µm nominal gaps form the variable capacitor. The shuttle mass is suspended from four corners with double 4-fold flexure beams. Device dimensions and other properties are shown in table 1. The fabrication process is illustrated in figure 3a and a completed device is shown in figure 3b. The deposition of thin film stopper (parylene) was carried out with a shadow mask (step 8), after the devices were cleaved. The thickness of parylene was 200 nm, as determined afterward with a profilometer. Following this the devices where wire bonded and packaged in a similar manner as reported in [9].

| Property               | Symbol | Value | Unit       |
|------------------------|--------|-------|------------|
| Die size               |        | 13x14 | mm x mm    |
| Shuttle area size      |        | 9.3 x 8.4 | mm x mm |
| Shuttle mass           | m      | 90    | miligrams  |
| Electrode overlap length |   Lf   | 400   | µm         |
| Electrode width        | Wf     | 8     | µm         |
| Nominal gap            | g0     | 22    | µm         |
| Number of electrodes   | n      | 336   |            |
| Spring beam width      | ws     | 10    | µm         |
| Spring beam length     | ls     | 1670  | µm         |
| Total stiffness        | k      | 14.6  | N/m²       |

4. Results

First the static capacitance of the device was measured using an LCZ meter. The nominal capacitance was found to be 30.7 pF, close to the analytical estimation of 25 pF. Next, determination of the frequency response, including the effect of the biasing voltage, was carried out. Figure 4 shows the

![Graphs showing PSD as function of frequency for different locations of the accelerometer on HVAC duct.](image)
results of a frequency up-sweeps conducted at 20 mg acceleration with the device connected to a series resistance of 3 MΩ. The output shows an increase in the nonlinear spring softening as the bias voltage increases (left shifting peaks), and spring hardening due to mechanical impact with stoppers (right slanting plateau with drop off effect).

Figure 3. (a) Fabrication process flow. (b) Completed device with parylene on electrodes.

Figure 4. Voltage across load resistor during vibration frequency up sweeps at 20 mg RMS amplitude and with various DC bias voltages.

Figure 5. MEMS device being tested on HVAC air duct.

Next, measurements were taken with the device on HVAC ducts hanging from the ceiling of the lab. An L-bracket was used to mount the harvester on the duct sidewall with its orientation normal to the duct wall where the vibration amplitude is maximum (figure 5). The raw data from the acceleration and voltage measurements is shown in figure 6. The peak power for a device biased at 15 V is 12 nW (0.6 nW RMS) at an RMS acceleration of 155 mg. The power spectral density (PSD) of the device is greatest at 240 Hz (6.9e-11 W/Hz) as shown in figure 7. This frequency corresponds to four times the
acceleration peak, 60 Hz and 7.15e-2 g^2/Hz, indicating that the device is operating in impact mode with the stoppers. Theoretically the devices were expected to reach significantly higher power, but the performance was significantly decreased due to a steep sidewall profile of the electrodes which prevented the devices from reaching a uniform minimum gap, reducing the maximum achievable capacitance. The sidewall profile was due to limitations associated with the etch tool. As an example, under static conditions, the trench for the nominal gap started with a width of 22 µm on top and reduced to 16 µm at the bottom of the 200 µm etch. Regardless, even with these imperfections, the device performed well, or better, when compared to similar harvesters working under the same range of broadband vibrations reported in literature [3,4,6,8].

Figure 6. Raw data from the device biased at 15 V and accelerometer attached to the HVAC duct.

Figure 7. PSD of acceleration and device voltage when on HVAC duct with 15 V bias.

5. Conclusion.
Energy harvesting from ambient vibration is of interest for powering sensors in building automation systems. In this work an electrostatic energy harvester using a gap-closing, interdigitated variable capacitor structure was designed for HVAC vibration power harvesting and tested. To maximize the power output of the device, a dual-level stopper system was incorporated, fixing the minimum gap in the nanometer range. When tested on HVAC air ducts of a laboratory in a large building the devices reached 12 nW of peak power, one of the highest reported power levels for similar devices working under equivalent conditions.

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