Flexible electret energy harvesters with parylene electret on PDMS substrates

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Flexible electret energy harvesters with parylene electret on PDMS substrates

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Abstract. Currently, most vibrational energy harvesters have rigid and resonant structures to harvest energy from periodic motions in specific directions. However, in some situations the motion is random and aperiodic; or the targeted energy source is the strain energy in deformation, rather than the kinetic energy in vibration. Therefore we propose and demonstrate a PDMS-based flexible energy harvester with parylene-C electret that can be attached to any deformable surfaces to harvest the stain energy caused by external deformation. The proposed flexible harvester was fabricated and characterized. The measured power at 20 Hz is 0.18 μW and 82 nW in the compression and bending modes, respectively. Such a harvester has the potential for wearable and implantable electronics applications.

1. Introduction

Due to the advance in low-power VLSI technology, the power consumption of integrated circuits can be reduced to the μW or sub-μW levels. Therefore it becomes feasible to power these electronic circuits by harvesting energy in the environment. The most common energy source for harvesting is the vibration or movement of buildings, machinery, and human bodies. Currently, most vibrational energy harvesters have rigid and resonant structures to harvest energy from periodic motions in specific directions. In some situations, however, the motion is random and aperiodic; or the targeted energy source is the strain energy in deformation, rather than the kinetic energy in vibration. To harvest the energy from a deformed object such as human body, flexibility of the harvesters is essential. Flexible energy harvesters have been demonstrated by using piezoelectric thin films deposited on flexible substrates [1, 2] or micro-structured PDMS with voids for charge storage [3]. However, piezoelectric materials and their preparation are not compatible to the conventional IC processes in general. Therefore, in this paper we propose and demonstrate a flexible electret-based energy harvester that is more compatible to the IC process and thus has a lower cost of fabrication.

2. Principle and design

Electret harvesters are capacitive harvesters that are biased by the semi-permanent charge in the electret material [4-7]. They convert the mechanical energy due to displacement or deformation into electrical energy stored in a variable capacitor. The principle of a typical gap-closing electret harvester is shown in figure 1. When the gap between the upper electrode and the electret is reduced due to

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external force or deformation, the induced charge on electrode increases and represents a current flow through the external load. The gap-closing configuration has the advantage of robust structure, simple fabrication processes and thus low cost. The flexibility is achieved by using flexible PDMS substrates for the electrodes and flexible parylene thin film deposited on the electrode as the electret material. Thus it can be compressed or bended to change the electrode gap.

The harvester has a capacitor area of 1 cm × 1 cm and gap of 1 mm. The Ansys simulation of the device upon compression (figure 2) shows that the deformation occurs only in the region close the spacer. The gap distance remains constant across most of the capacitor area. Therefore this device can be regarded as a simple variable parallel-plate capacitor upon compression. Figure 3 shows the measured and calculated load force vs. displacement. For a load of 32 N, the displacement is about 0.8 mm and thus the capacitor gap is reduced to 0.2 mm. The force-displacement relationship in figure 3 is used in a Simulink model to simulate the output of the harvester for various applied force, frequency, and loading resistance [6, 7]. Figure 4 shows the simulated output power for applied displacement of 0.8 mm and load resistance of 1000 MΩ for various excitation frequency. The output power increases quadratically with frequency, indicating that the harvester can be modelled as a constant current source in this quasi-static operation condition.

3. Device fabrication

Figure 5 shows the fabrication processes of the proposed flexible electret harvester. First, the 1-mm-thick PDMS substrates were cast by using an acrylic mold. Al/Cr electrodes were then deposited on the substrate by sputtering (Figure 5(a)). A 1-mm-thick cast PDMS spacer was then bonded to the metalized electrode (Figure 5(b)). A 5-μm-thick parylene-C as the electret layer was then coated on top of the metal layer. Electret charge was deposited on the parylene layer by corona discharge at 100 °C with V_{needle} = -4 kV and V_{grid} = -500 V (Figure 5(c)). Finally, another metalized PDMS electrode

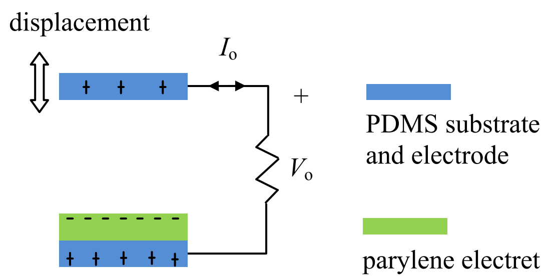


Figure 1. Schematic of the proposed flexible energy harvester.

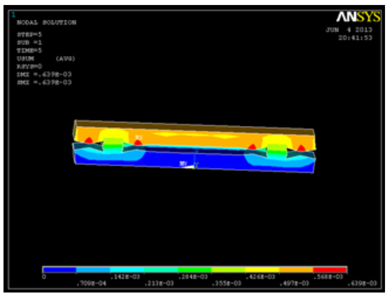


Figure 2. Ansys simulation of the flexible harvester.

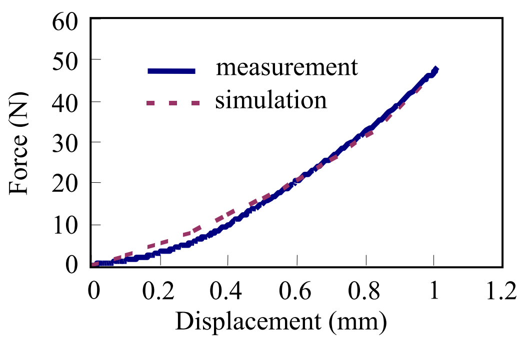


Figure 3. Measured and calculated force-displacement relationship.

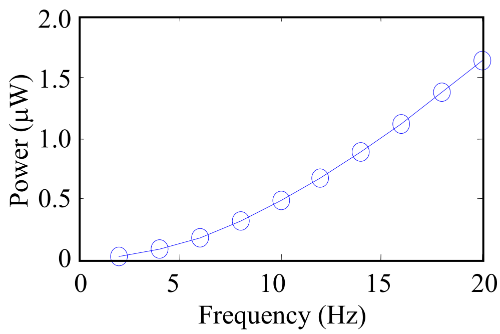


Figure 4. Simulink simulation of the harvester output.

was bonded to the bottom structure and served as the upper electrode (Figure 5(d)). Figure 6 shows the assembled and packaged harvester. Figure 7 shows the stability of the parylene-C electret. The surface potential is -227 V (64% of the initial value) after 7 months of charging, which is comparable to the data in [8]. It is noted that the surface potential was stabilized after the initial decay within one hour of charging and maintained about 10% fluctuation for the rest of the measurement period.

4. Measurement and discussion

A Bose Electroforce 3200 dynamic mechanical analyzer (DMA) (figure 8(a)) was used to apply a sinusoidal displacement on the device for mechanical and electrical characterization. A normal displacement was first applied to measure the device output in response to the compressive force (figure 8(b)). The measured open-circuit output voltage for 2-Hz displacement with 0.8-mm stroke and 1000-MΩ load is shown in figure 9. Higher excitation frequency induces more current and power. Figure 10 shows the output power vs. frequency for a 0.8-mm displacement and 1000-MΩ load resistance. The maximum power of 0.18 μW is obtained at 20 Hz.

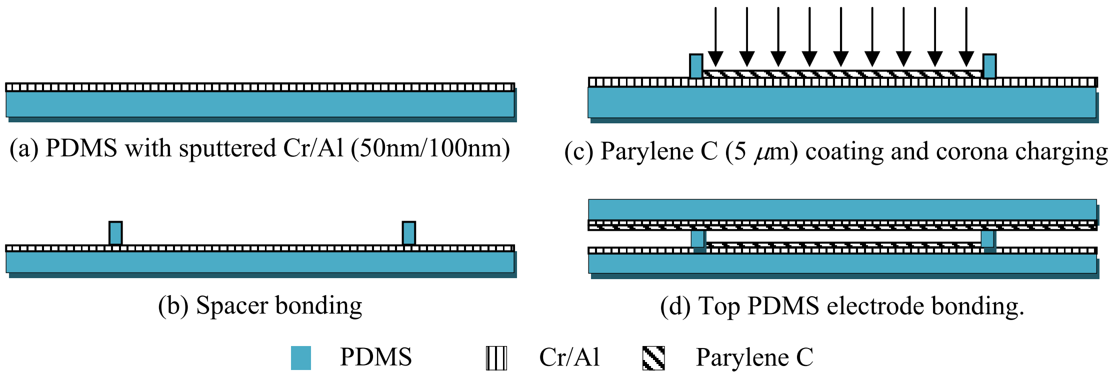


Figure 5. Fabrication processes of the proposed harvester.

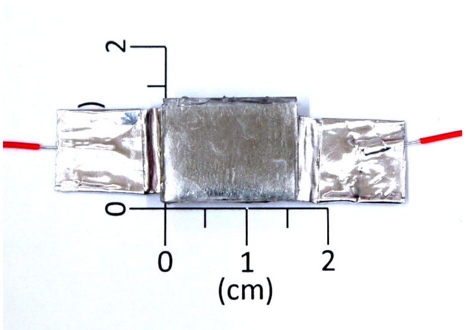


Figure 6. Photograph of assembled harvester.

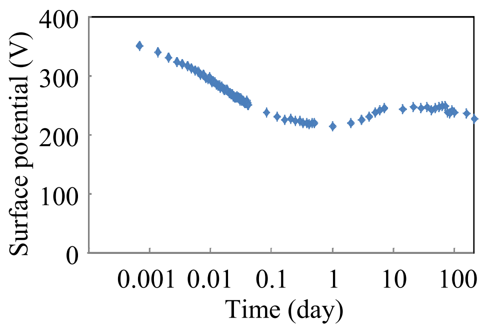
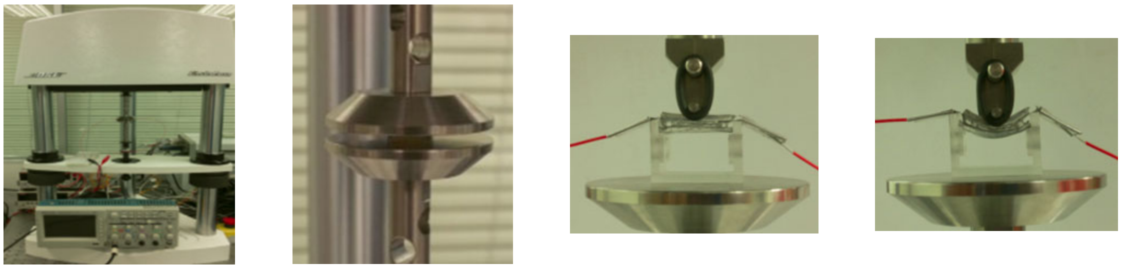


Figure 7.Charge stability of parylene-C electret.



(a) (b) (c) (d)

Figure 8. (a) Dynamic mechanical analyzer, (b) compression test, (c) and (d) bending test.

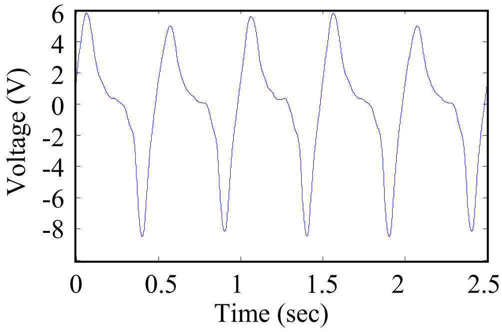


Figure 9. Output voltage for 0.8-mm compressive displacement at 2 Hz.

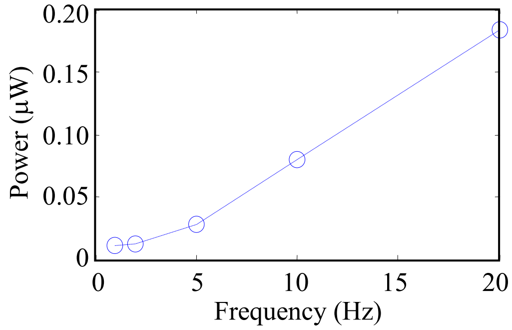


Figure 10. Output power vs. load for 0.8-mm displacement.

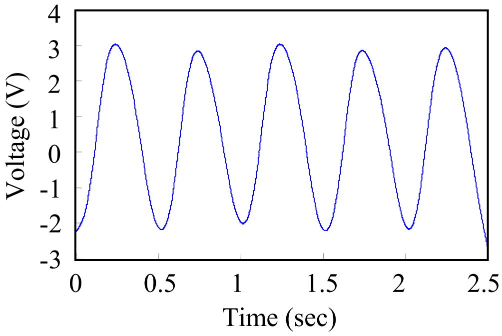


Figure 11. Output voltage in bending test (stroke = 3mm).

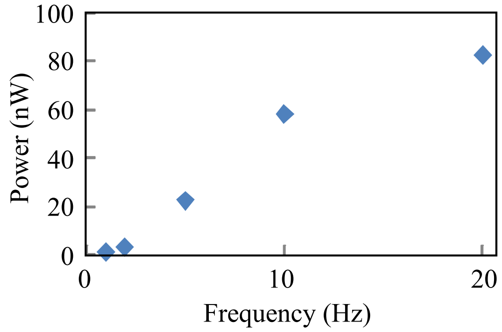


Figure 12. Output power in bending test (stroke = 3 mm).

The flexible harvester was also tested in bending situations as shown in figures 8(c)-(d) to simulate the bending of body parts such as arms or legs. The harvester was placed in a test fixture and the DMA applied a displacement at the middle of the harvester to bend it. Figure 11 shows the output voltage for a 3-mm stroke of DMA at 2 Hz. The output power for various frequency is shown in figure 12. Since the two ends of the harvester placed in the test fixture were not fixed, the required external force was relatively small and thus the power was reduced compared to that in the compressive test. The maximum power of 82 nW is obtained at 20 Hz in the bending test.

The demonstrated flexible harvester generates an output current when compressed or deformed because of the variation of the electret-induced charge on the electrodes. Therefore, it can also be regarded as a piezoelectric structure. The effective piezoelectric d_{33} coefficient can be estimated from the measured output power, assuming uniform force and charge density, to be

$$d_{33} = \frac{\Delta Q / A}{F / A} = \frac{\sqrt{2P / R\omega^2}}{F} = 12.8 \text{ pC/N},$$

where ΔQ is the charge variation, F is the applied force, A is the device area, P is the rms output power, R is the load resistance, and $\omega = 2\pi f$ is the angular frequency. The calculated d_{33} coefficient is low compared to that reported in [3, 4] where the implanted charge is stored in the micro voids in polymer substrates. Further optimization of our current design can improved the piezoelectric property.

5. Conclusion

In conclusion, a flexible PDMS electret energy harvester with stable parylene-C electret has been demonstrated. The measured power at 20 Hz is 0.18 μW and 82 nW in the compression and bending modes, respectively. Further optimization of the device design and fabrication processes can improve the output power and piezoelectric coefficient.

Acknowledgements
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