Flexible Electret Energy Harvester with Copper Mesh Electrodes

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Abstract. Flexible energy harvesters are desired in biomedical applications since human motion is often complicated and aperiodic. However, most demonstrated flexible energy harvesters employ piezoelectric materials which are not biocompatible. Therefore we propose a PDMS-based flexible energy harvester with Parylene-C electret suitable for biomedical applications. To address the reliability issues of sputtered metal electrodes, we use copper mesh electrodes to improve the reliability. The proposed flexible harvester was fabricated and characterized. The measured power of the proposed harvester was 3.33 μW in the compression tests at 20 Hz and 8.5 nW in the finger bending tests at 2 Hz.

1. Introduction

When energy harvesters are used in biomedical applications such as physiological monitoring or human gesture detection [1], flexible harvesters are advantageous since human motion is often complicated and aperiodic. Flexible energy harvesters have been demonstrated by using piezoelectric materials [2, 3]; however, piezoelectric materials are not IC-process compatible nor biocompatible. In [4], we have demonstrated a flexible electret energy harvester based on biocompatible PDMS and Parylene. However, the sputter-deposited metal electrodes were prone to cracks upon the bending and stretching of the flexible substrate. To improve the reliability of the electrodes, we propose and demonstrate a flexible electret energy harvester with embedded copper mesh as the electrodes in this paper. The electrode reliability and the output power of the fabricated harvester are presented.

2. Principle and design

Figure 1(a) shows the schematic view of the proposed harvester composed of two PDMS electrode layers and a spacer layer. The device is a gap-closing capacitive harvester biased by Parylene electret. The gap-closing type is featured with robust structure, simple fabrication processes and thus low cost. Copper mesh is embedded in the electrode layers for electric connection and to improve electrode reliability. The copper mesh is made of copper wires with 50-μm diameter and has 200 meshes per inch, as shown in Figure 1(b). When an external force is applied to the harvester, the gap between the electrodes is changed and thus an output current is induced. Since the deformation of the PDMS structure can be large for large applied force, the nonlinear force-displacement relationship of the device was measured, as shown in Figure 1(c), and used in the electromechanical simulation of power generation. The capacitance area of the proposed harvester is 1 cm × 1 cm and the initial gap is 1 mm.
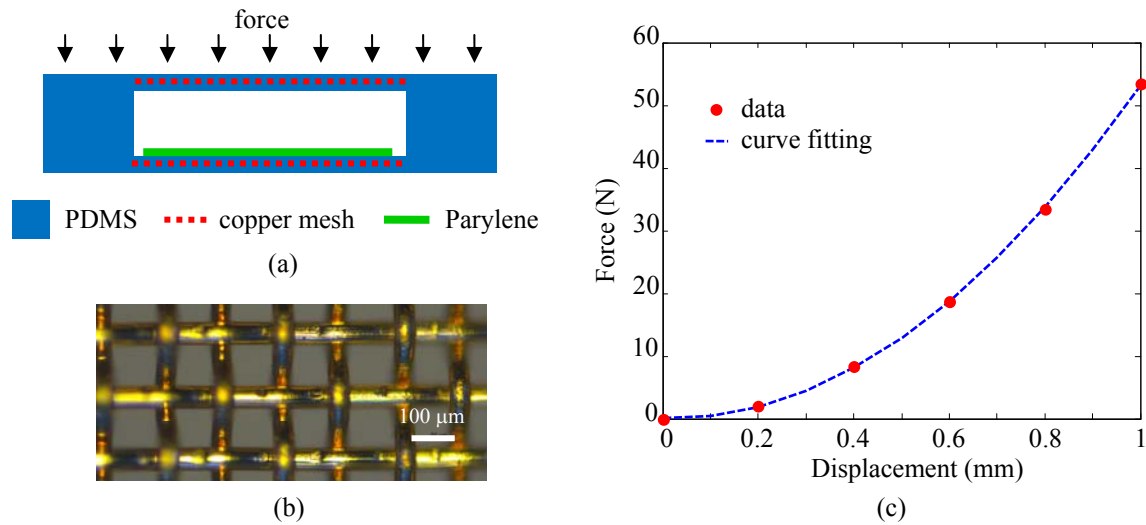
Figure 1. (a) Schematic of proposed flexible harvester, (b) photograph of copper mesh, (c) force-displacement relationship of fabricated device.
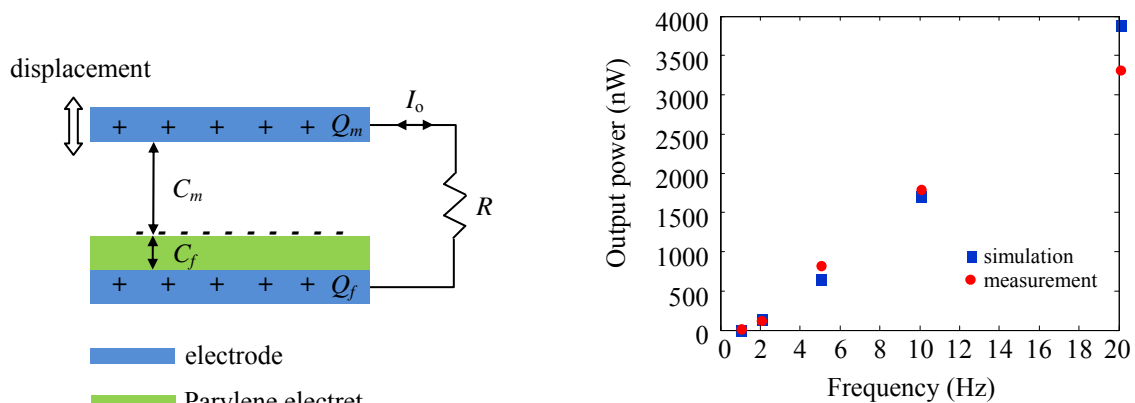

Figure 2. Electrical model of harvester.

Figure 3. Simulated and measured power with 1000-MΩ load.

The electrical model of the harvester is shown in Figure 2. The output current induced by the time-varying capacitance is given by

$$I_0 = -\frac{dQ_m(t)}{dt} = -\frac{V_{suf}}{R} + \frac{Q_m(t)}{RC_{eq}(t)},$$

where V_{suf} is the surface potential of the electret, C_{eq} is the total capacitance of C_m and C_f connected in series, and Q_m is the charge on the movable electrode. Since the equation is a complex electro-mechanically coupled differential equation, the output current and power were estimated by Simulink simulation, as shown in Figure 3.

3. Device fabrication

The fabrication processes of the proposed energy harvester are shown in Figure 4. First, flexible electrodes were fabricated by casting PDMS between two glass substrates with the copper mesh sandwiched in between. After curing, the copper mesh was embedded in the PDMS flexible electrodes. (Figure 4(a)). The total thickness of the electrodes was controlled by a feeler gauge during the casting to be 250 μm. A 5-μm-thick Parylene-C was then coated on the cured electrodes as the electret layer (Figure 4(b)). A 1-mm-thick PDMS spacer was then bonded to the electrode (Figure 4(b)). The

electret was charged by corona discharging at 100 °C with -4 kV needle voltage and -500 V grid voltage (Figure 4(c)). Finally, another electrode was bonded to the top of the spacer (Figure 4(d)). Figure 5 is the photograph of a fabricated harvester with soldered leads. The long term charge stability of Parylene-C electret on PDMS substrate in this process is shown in Figure 6. After 724 days of charging, the surface potential decayed to about 52% of the initial value, comparable to the data in [5].

(a) PDMS electrode with embedded copper mesh   (b) Parylene coating and spacer bonding

(c) corona charging   (d) Top electrode bonding

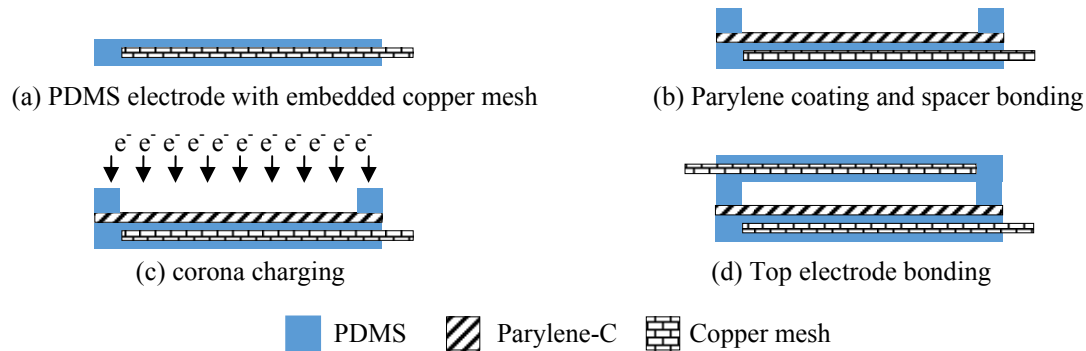PDMS   Parylene-C   Copper mesh

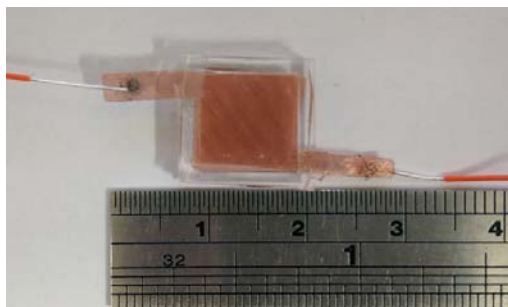Figure 4. Fabrication processes.

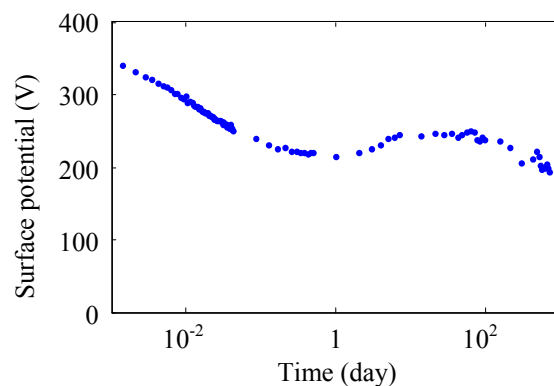
Figure 5. Photograph of a fabricated harvester.

Figure 6. Measured surface potential of Parylene-C electret on PDMS

4. Measurement and discussion

4.1. Electrode reliability

Two types of electrodes were prepared for reliability test. Figure 7(a) shows a 1 cm × 1cm PDMS electrode with embedded copper mesh; Figure 7(b) shows a 1 cm × 1cm 100-µm-thick PDMS electrode with 0.5-µm-thick sputtered aluminium on the surface. Both types of electrodes were attached to another 1 cm × 2 cm 1-mm-thickness PDMS substrates and then placed on a C-shaped acrylic test fixture (Figure 7(c)). The test fixture was loaded in a Bose Electroforce 3200 dynamic mechanical analyzer (DMA) which applied a 5 Hz and 3-mm displacement at the center of the test samples. In this pure bending test, the metal electrode experienced a tension force. Figure 8(a) shows the circuit used to characterize the electric conduction of the electrode. If electric conduction is good, the 1-V DC bias can be observed on the oscilloscope; if the conduction deteriorates, the observed voltage will decrease. For the copper-mesh electrode, the observed voltage remains at the 1-V bias level during a 60-min test, indicating no degradation of conduction. For the sputtered-Al electrode, the recorded voltage started at the bias level but started to show fluctuation after 10 min of test. Figure 8(b) is the voltage after 12 min of test, showing significant electrode degradation. After 16 min of test, the sputtered-Al electrode became open-circuited and the oscilloscope showed a flat zero voltage signal.

Significant cracking of the Al electrode was observed on the surface after the 16-min test. The reliability of the copper mesh as an electrode material was thus confirmed.
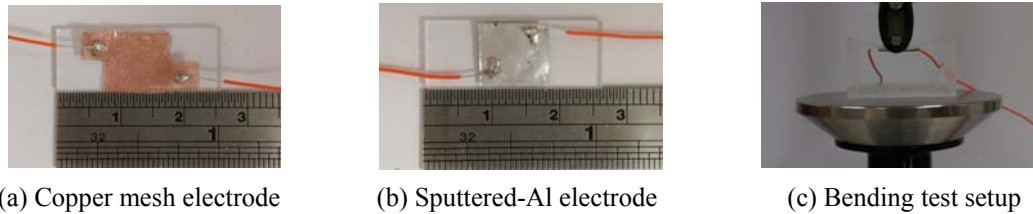

(a) Copper mesh electrode   (b) Sputtered-Al electrode   (c) Bending test setup

Figure 7. Electrode reliability test samples and setup.

(a)   (b)

Figure 8. (a) Electrode reliability test circuit, (b) observed signal for sputter-Al electrode after 12 min of test.

4.2. Power generation

Two power generation experiments were conducted. The DMA was first used to apply a uniform sinusoidal displacement on the device to mimic scavenging energy from periodic human activity such as walking or running. The measured output with 1.0-mm stroke on a 1000-MΩ load agreed with the simulation well, as shown in Figure 3. The output power at 2 Hz is 0.13 µW; the power increases with frequency and reaches 3.33 µW at 20 Hz. The maximum output power density was estimated to be 15.4 µW/cm^{-3}. The linear increase of power with the frequency implies that the harvester can be modeled as a constant energy source per cycle at low output levels. Figure 9 shows the simulated and measured output power vs. load at 2 Hz. At such low frequency, the output capacitive impedance of the harvester and thus the optimum load are very large, as shown in Figure 9. Thus, proper power conditioning circuits are needed to match the load to the harvester to improve the power transfer efficiency.

In the second experiment, the harvester was attached to a human finger knuckle to scavenging energy from the finger motion. Figure 10 shows the experimental setup and measured output voltage. The angle of finger bending was about 90°. With a 1000-MΩ load, the output power was 8.36 nW for a harvester with electret surface potential of 350 V. The experiment demonstrated that the proposed harvester could scavenge energy from human motions or when attach to deformable surfaces. The low power output was due in part to the low actuation frequency and in part to the low effective area utilized in the bending deformation as compared to compression.

5. Conclusion

This paper presents a flexible electret energy harvester with robust copper mesh electrodes. The measured power was 3.33 µW in compression tests at 20 Hz and 8.36 nW in human finger tests at

about 2 Hz. With further optimization of the device design and fabrication processes, improved output power levels can be expected.
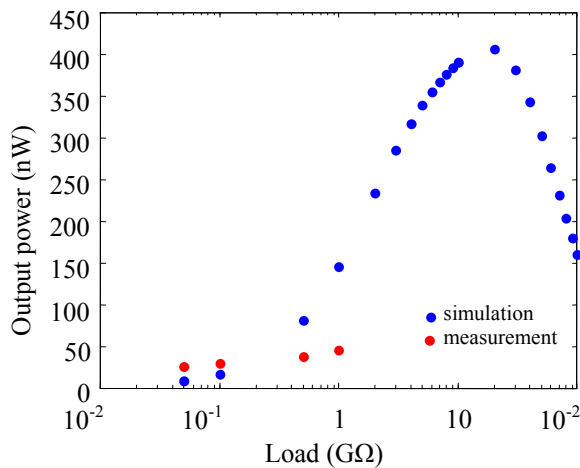

Figure 9. Simulated and measured output power with various loads at 2 Hz.
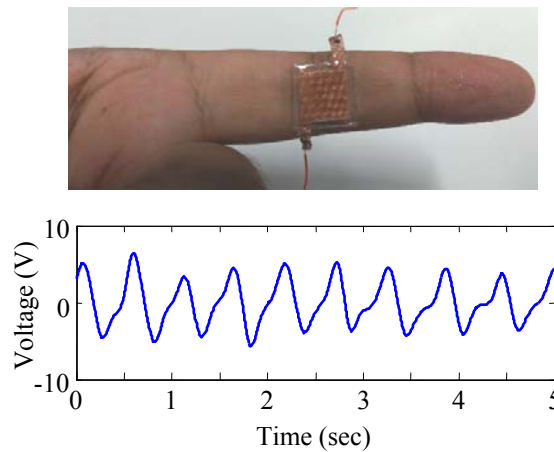

Figure 10. Testing of harvester attached to a human finger.

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