MEMS Energy Harvester for Wireless Biosensors

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ABSTRACT

This paper reports a motion energy harvester integrated with a battery-less wireless transmitter, and the successful transmission of low power pulses representing sensor data. An electrostatic harvester, primed by voltage representing sensor data, delivers output pulses to a resonant transmitter with an integrated antenna. This is the first ever reported demonstration, to our knowledge, of wireless sensor transmission solely powered by MEMS energy harvesting devices.

INTRODUCTION

The topic of energy harvesting has been widely studied, and various types of energy harvesters have been reported. Generally they can be classified as non-motion driven, including solar [1], RF [2] etc, and motion driven. Since mechanical vibration is probably the most versatile energy source, the majority of research works have fallen into the latter category. Some generators are used as an auxiliary for rechargeable batteries [3] to extend their life span. Others can be used alone to power wireless sensors [4]. In the field of medical devices, energy harvesting is an attractive option for powering implanted biosensors, to avoid battery recharging and replacement [5] and since light and significant temperature differences are not available, motion is the more suitable source. However, at the millimetre scale of MEMS harvesters, even the theoretically achievable power levels from reasonable body motion amplitudes are in the sub-microwatt range. Thus, although small wireless sensors powered by motion harvesters have been reported (e.g. [6]), the harvesters are relatively large, non-MEMS devices.

Inertial energy harvesters extract energy from motion by damping the internal motion of a proof mass suspended within the device, when the device is attached to a moving host. The damping is done by a transducer, typically electromagnetic, electrostatic or piezoelectric, from which the harvested power is obtained. One limitation of MEMS motion energy harvesters is the limited proof mass, and thus power output, that can be achieved by a monolithic device. Previously we have reported an electrostatic motion harvester using an external proof mass, in the form of a rolling cylinder, rather than a mass machined from the substrate material, in order to enhance the achievable output power [7]. We report here, for the first time, a device of this kind based on a flexible substrate. Electrostatic harvesters require priming charges (or electrets) to function. Previously we have introduced a new device architecture concept, in which a biosensor provides this priming voltage, and the harvester amplifies this signal to power a transmitter [8]. Here we also report, for the first time, the successful implementation of such a device.

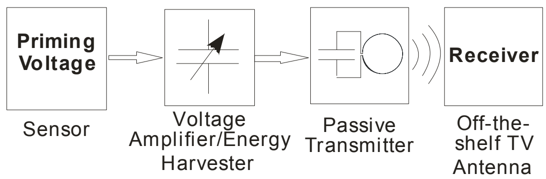

Figure 1: Schematic illustrating working principle.

Fig. 1 illustrates the architecture. A voltage output sensor, such as a thermopile or potentiometric pH sensor, provides the priming input to a variable capacitor of which the proof mass forms one electrode. The motion source moves the mass off the charging contacts and away from the counter-electrode, reducing the capacitance and thus increasing the stored energy. The mass then contacts a discharging terminal, and the harvested energy is thus dumped into a resonant tank of which the inductor is also the antenna. The resulting pulse is received by a remote antenna, and its amplitude is proportional to the priming voltage and thus indicates the sensor's output. The energy harvester can also be seen as a voltage amplifier. It amplifies the input voltage from the sensor by a fixed ratio. This ratio is determined by the maximum to minimum capacitance ratio of the harvester.

Fig. 2(B) shows the structure of a complete device, including ground plane, dielectric layer, charging and discharging contacts, and loop antenna. The capacitor is pre-charged when the rod lies on top of the input contacts at the front, and discharged when it lies above the output contacts between any successive plates. Multiple pulses are transmitted each time the device is excited mechanically. No battery is needed, nor any additional circuitry since the moving mass also provides the switching, self-

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synchronously. Compared to our previously reported moving plate harvester, Fig. 2(A), the new device benefits from a much heavier external mass and multiple output pulses on each mechanical cycle. The energy harvested is proportional to the mass, and the multiple output pulses of reduced voltage make them more suitable for standard off-the-shelf electronics.

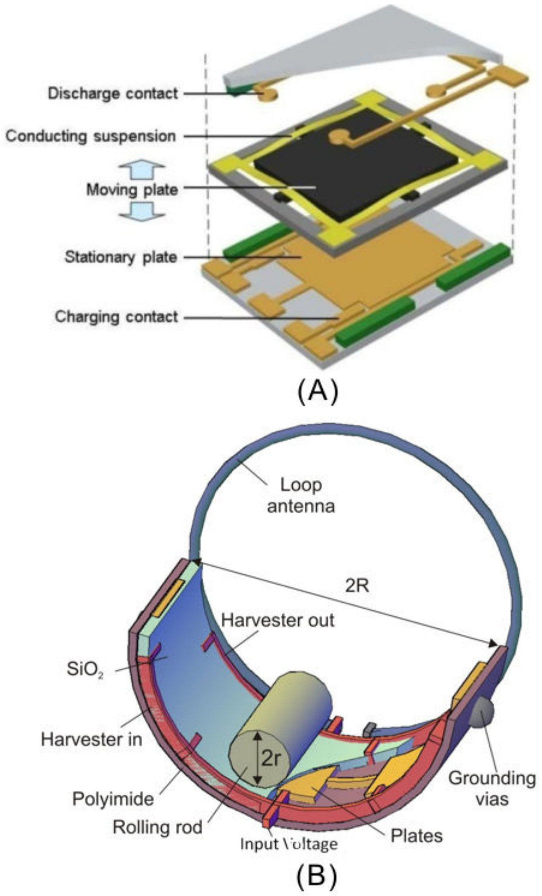

Figure 2: 3D models of electrostatic energy harvesters: (A) Moving plate [5] *(B) Rolling Rod.*

ANALYSIS

The mechanism behind the generator is straightforward. The capacitor is charged by the priming voltage at maximum capacitance positions, and discharged at minimum capacitance positions. Since charge stored on the capacitor is conserved during the transition, the voltage difference between the electrode pair rises as described by $V = Q/C$. Energy-wise, work is done against the electrostatic attraction between the rod and its counter electrodes. Energy is transformed from mechanical motion to electrical charge storage. This energy is then released through output contacts when the rod rolls over them.

Simple analysis shows that the maximum electrical energy extracted from the rod's motion is proportional to the product of the ratio and the difference between the max and min capacitance. This is shown in equation (1), where V_{pri} stands for the priming voltage.

$$\Delta E = \frac{1}{2} V_{pri}{}^2 \frac{C_{max}}{C_{min}} (C_{max} - C_{min}) \qquad (1)$$

The smallest practical C_{min} is limited by the parasitic capacitance, because any effective electrode capacitance is in parallel with it. Thus if the minimum electrode capacitance is too small, the parasitic capacitance will dominate. The parasitic capacitance can vary between sub pF to a few pF. The desirable trade-off is to keep the minimum capacitance above this parasitic level, while still maintaining a high ratio between the max and min capacitance, within the size constraints. Consequently maximising both capacitances while keeping a large ratio between them is critical to the performance of electrostatic harvesters.

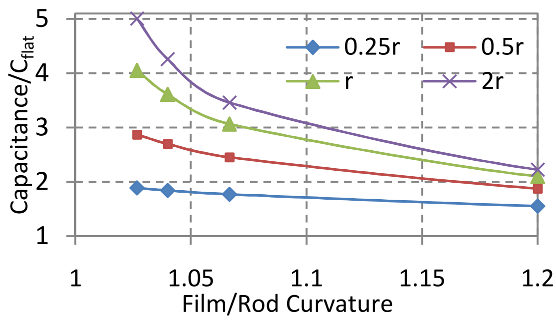

Figure 3: Finite-element simulation of rod-to-plate capacitance versus substrate curvature for different plate widths as shown. The capacitance and the curvature are normalized to the flat-substrate capacitance and the rod radius respectively.

By curving the substrate, some increase in peak capacitance is obtained (Fig. 3), and the position of the mass is better constrained this way. Most of the capacitance gain comes in the region when the radius of polyimide film is close to that of the rod. Our prototype only has an average gain of 1.5 due to its large film curvature. This can be conveniently increased by curving the film further. As both axes have normalized units, the plot gives a generalised guide for the effect of curling the substrate on the maximum capacitance in electrostatic devices.

FABRICATION

Fig. 4 shows the major steps of the process flow, with photoresist (PR) steps omitted. Firstly three layers of materials, Cr, Cu and SiO_2, are sputtered onto the polyimide film (step 1). The Cr layer is for adhesion; The Cu is the bottom electrode layer; SiO_2 is for electrical isolation. Then PR is coated and patterned to expose the contacts region. The SiO_2 layer is removed in the exposed region with Reactive Ion Etching (RIE) (step 2), followed by Cu electroplating (step 3). The purpose of the electrodeposition is to raise the contact slightly above their surroundings so that charge and discharge occur more smoothly when the rod rolls over them. After that, a second lithography step is implemented to cover only the contacts and bottom electrode regions. Again, the exposed SiO_2 layer is etched off by RIE (step 4). Then the whole wafer is soaked in Cu and Cr etchants one after another to remove the unwanted metal layers (step 5).

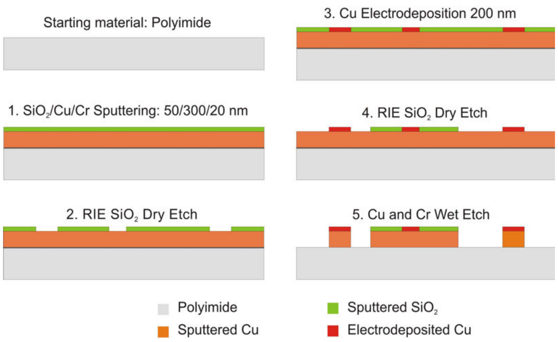

Figure 4: Process flow of the harvester fabrication.

During the whole process, the polyimide substrate is supported by another glass wafer because the film itself is too soft to maintain a flat shape through these operations. Therefore it is bonded onto the glass wafer with Kapton tape around the edges and removed at the end of the whole process.

The quality of the SiO_2 layer is crucial to the success of the device. Any pinholes on the dielectric layer will discharge the capacitor before the rod reaches the designed discharge contacts. The thickness and uniformity of the SiO_2 layer together with the roughness of the rod contribute significantly to the capacitance value. Fig. 5 shows a cross section of the sputtered layers. The 50 nm SiO_2 thickness is chosen to ensure absence of pinholes while maximizing the capacitance.

Fig. 6 shows a complete die with a steel rod proof mass. The polyimide substrate is 6 × 14 mm. The steel rod has radius of 1.25 mm and length of 4 mm. The inset picture is captured from a Zygo optical interferometer. The red region indicates that the contacts are indeed higher than the bottom electrodes (green). The smoothness of the surface is satisfactory. Nonetheless minor film bending at local regions does occur (The gradual colour transition, from green to yellow, on the plate). This is inevitable due to the nature of the film.

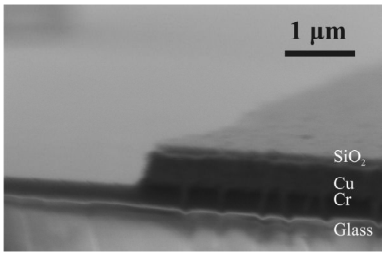

Figure 5: SEM image of sputtered Cr/Cu/SiO2 multi-layers for one plate of the device.

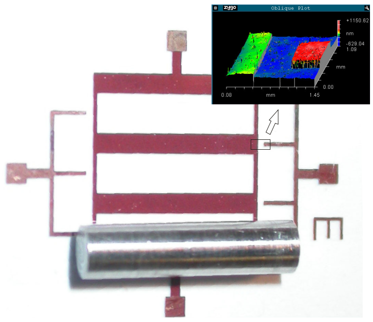

Figure 6: Optical image of the MEMS device. Inset: Optical interferometry measurement of the surface topology.

TESTING RESULTS

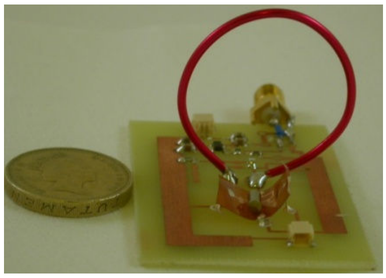

Figure 7: Photograph of a test module.

The harvester and loop antenna are mounted on a larger test substrate (Fig. 7), with a one pound coin for size comparison. The 2 cm diameter loop is designed for a transmission frequency of 350 MHz; use of higher frequencies (>1GHz) will allow this to be reduced in future to match the harvester dimensions. The circuit on the test substrate has three functionalities: priming the capacitor, passing the output pulse to the loop antenna and to an op-amp in inverted setup for oscilloscope measurements. The device was mechanically excited by impulses of about 1 mN, which cause about 6 ms^{-2} of acceleration on the rod. The rod oscillates at 5-10 Hz frequency for a few seconds before the amplitude dies off. This corresponds some tens of oscillations. Voltage priming was provided by an external source representing the sensor output, allowing the relation between sensor and received signal amplitudes to be demonstrated.

Fig. 8 shows examples of transmitted and received pulses, using an antenna separation of 20 cm. Priming voltages as low as 2 V were applied; this corresponds to pulse energies below 1 nJ. The received signal follows the envelope of the transmitted signal, which indicates good amplitude translation. The amplitudes of the received signal vary with separation and orientation of the two antennas. The slight time delay comes from the receiver's response time. An off-the-shelf TV antenna was selected to capture the transmitted signal for its broad reception bandwidth.

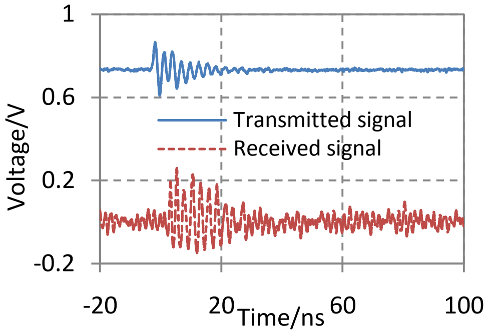

Figure 8: Example of transmitted and received pulses, at around 350 MHz. Receiver is placed 20 cm away from the transmitter.

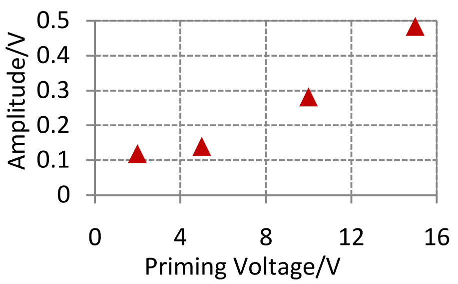

Figure 9: Detected signal amplitude versus priming voltage (reception distance 20 cm).

Multiple measurements were taken and the amplitudes of received signals were plotted against priming voltages, as shown in Fig. 9. The linearity is good for all but the lowest value.

DISCUSSION

In practice, the amplitude of the received signal is greatly affected by the distance between the transmitter and receiver and the orientation of the receiver antenna. In order to extract reliable information a pre-defined reference signal could be employed to prime the voltage amplifier on alternate output contacts. The amplitude of the data signals can then be compared with that of the reference pulses to calibrate the response. The correct priming (sensor) voltages can thus be extracted.

The linearity of the received signal to priming voltage is not ideal when the priming voltage is low. This may be because additional charge is created through friction during the rod motion. This needs further investigation. Also, the required priming voltages are high compared to typical outputs from potentiometric sensors. Increasing C_{max} would help reduce this requirement.

To summarize, a wireless biosensor module solely powered by a MEMS motion energy harvester, and suited to sensors with voltage output, is reported for the first time.

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