Non-Resonant Electrostatic Energy Harvesting from a Rolling Mass

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***Abstract*—Energy harvesting devices typically have a resonance frequency at which optimum power transduction is achieved. This is impractical for power sources with low or broad frequency ranges, such as human motion. Previously, a novel, non-resonant electrostatic energy harvesting device was proposed, using an external proof mass in the form of a rolling cylinder. Substrate parasitic capacitance was identified as a key issue for successful device operation. In this paper, a new fabrication method is presented. Parasitic capacitance effects are reduced using glass instead of silicon as a substrate. A scalable fabrication technique for contact–to–dielectric alignment below 100 nm using electrodeposition was developed. Initial devoce characterization shows output power for the first time, with some voltage gain. Further improvements on the fabrication and characterization techniques are proposed which may lead to consistent, non-resonant power transduction from human body motion or other power sources. Implementation concepts are outlined.**

I. Introduction

Energy harvesting devices are attractive for body mounted sensors, particularly for implanted devices where battery replacement is impractical. In the implantable case, since light is not available and temperature gradients are modest, ambient motion is a more suitable source of power. However, the low frequencies of body motion offer limited power densities [1], and since a high degree of miniaturization is desirable, achieving near-optimal designs will be necessary for these applications to be feasible.

A wide range of motion scavenging devices have been reported [2], [3]; most are based on a proof mass mounted to a frame with a flexible suspension, with power generated by damping the relative proof mass motion with a transducer element. These devices generally use resonant operation, which is unlikely to be optimal in this application given the broad and varying spectrum of body motion. We have previously reported silicon MEMS (micro-electro-mechanical systems) energy harvesters, having an integrated mass forming one element of a variable capacitor, with power derived from an electrostatic force between moving mass and frame [4]. Such a monolithic device is attractive for size and (potentially) cost reasons, but has several important limitations. Firstly, maximizing the proof mass necessitates machining through the full thickness of the wafer, which is incompatible with most integrated electronics processes. MEMS inertial sensors with monolithically integrated electronics are well established commercially, and are similar in structure to inertial energy harvesters, but typically use surface mounted proof masses of inadequate size for energy generation use. Furthermore, obtaining a substantial travel range with a monolithic device is difficult, as is a suspension which is highly flexible in the travel direction but prevents motion in other axes. For these reasons, we are developing a device which is suitable for on-chip integration, but using an external proof mass.

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II. Operating Principle

The operating principle of the device is illustrated in Figs. 1 and 2.

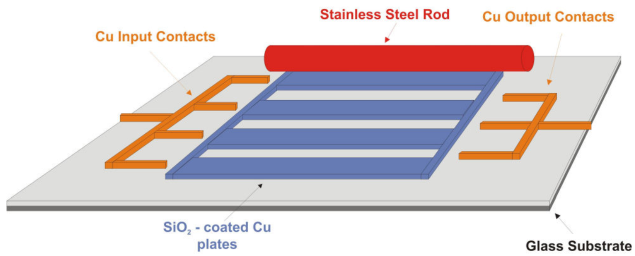

Fig. 1: Schematic illustrating physical construction of the device.

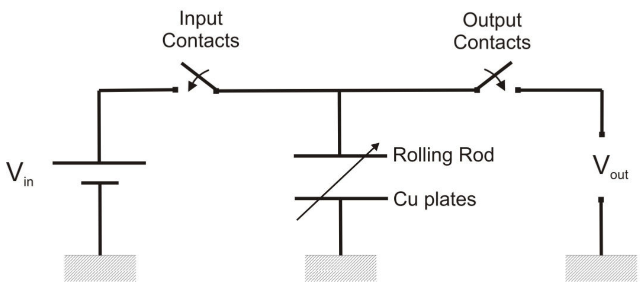

Fig. 2: Schematic circuit showing electrical operating principle.

The device uses electrostatic transduction as in [4]. A series of strip electrodes form the fixed plates of the variable capacitor, and are covered by a thin dielectric layer. A metal cylinder forms the moving counter-electrode. When the cylinder is aligned with one of the strip electrodes, it makes direct contact with an additional charging contact, by which the necessary pre-charge is applied. This creates an electrostatic force between the cylinder and the strip electrode. Motion of the substrate then induces rolling of the cylinder, causing it to break contact with the pre-charge supply; the separation is then increased at constant charge, so that as the capacitance reduces, the stored energy increases due to the work done against the electrostatic force. The cylinder then makes contact with a discharge electrode, releasing this energy in the form of a high voltage pulse. Compared to the monolithic device of [2] there are several key advantages: the proof mass can be significantly larger for an equivalent device size, since the out-of-plane dimension is not restricted to the wafer thickness; a material of density much higher than that of silicon can be used; no suspension structure is needed; the travel range (to which the achievable power is also proportional) is greatly increased; and the output is provided in several pulses per motion cycle, rather than a single one. The latter characteristic is valuable because parasitic capacitances typically make it difficult to benefit from a large motion range in a single pulse system.

III. Power Density

The power levels achievable from inertial harvesters have been extensively analysed [1]. They are limited by four parameters: the proof mass and internal motion amplitude of the device, m and Z_l, and the amplitude and frequency of the source motion, Y_o and ω (assuming harmonic source motion). The theoretical maximum for the harvested power is given by:

$$P_{max} = 2m\omega^3 Y_o Z_l / \pi \qquad (1)$$

Since frequency and source amplitude are fixed by the ambient motion, the design should maximize mass and travel range. For the monolithic device of [4], having a surface area of $\approx$ 1 cm^2, a proof mass volume of $\approx$ 0.05 cm^3 was achieved, and with the density of Si only 2.33 g/cm^3, this gave m = 0.12 g. The motion amplitude was $Z_l \approx$ 0.5 mm. These m and Z_l values will be similar for other silicon monolithic devices, whether using in-plane or out-of-plane motion. For the present device, the proof mass is a steel cylinder of length 1 cm and diameter 0.75 mm, giving m = 0.05 g, and the travel range is $\approx$ 1 cm. This gives an mZ_l product about 8× greater than in the monolithic case. Larger improvements are possible with larger rod diameters, at the expense of frequency range. For a source motion of frequency and amplitude 1 Hz and 10 cm respectively, this gives a maximum power of $\approx$ 8 μW, or a power density of 40 $\mu W/cm^3$, taking 2 mm for the total package height. Again, these values are 8× higher than for the fully monolithic case, and are adequate for many sensor types.

IV. Fabrication

Previously we described fabrication of a device using plated metal layers on Si substrates [5]. This device had problems of inadequate surface flatness, and excessive parasitic capacitance to the substrate. As a result, output pulses were not obtained from that device. Reaching theoretically achievable power levels in inertial energy harvesters depends on achieving high transduction forces, and for electrostatic devices this in turn requires high initial capacitance, and low parasitic capacitances. Consequently we have redeveloped the design and process flow, using insulating substrates, and reduced dielectric layer thickness to increase initial capacitance. Thus we report here, for the first time, the demonstration of output power from such a rolling mass energy harvester

The wafer-lever fabrication process for the improved device is described in Fig. 3. A 4 inch diameter, 500 μm thick Schott Borofloat33 glass wafer was used as the substrate. A 20 nm Cr adhesion layer and a 500 nm Cu layer were sputtered on the glass wafer, followed by a 100 nm SiO_2 dielectric layer, also deposited by sputtering (step 1 in Fig. 3). Using conventional photolithography, patterns of photoresist were defined on top, exposing only the contact areas of the devices (step 2 in Fig. 3).

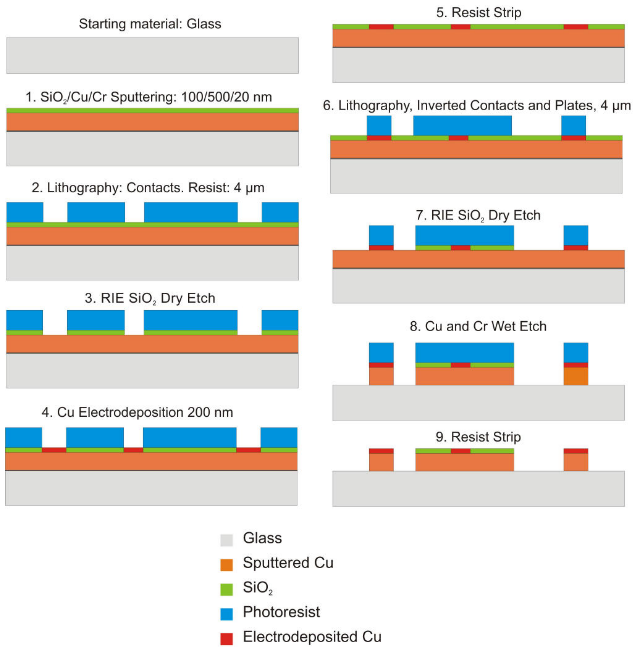

Fig. 3: Wafer processing for the fabrication of the rolling mass electrostatic generator.

The SiO_2 was etched at the contact areas using reactive ion etching (RIE), (step 3 in Fig. 3), and Cu electrodeposition followed, to a thickness of 200 nm (step 4 in Fig. 3). This technique is promising for much finer calibration at the edge between the SiO_2 and the Cu contact. Subsequently, the resist was stripped off the wafer and a new resist pattern was defined to cover the plate and contact regions of the device (step 6, Fig. 3). The SiO_2 was etched using RIE and the Cu and Cr were etched using appropriate chemical etchants. The wafer was sawn into die containing one device each, to allow individual device testing.

The external mass used was a steel rod with diameter 0.75 mm. An optical image of the device is shown in Fig. 4. The electroplated contacts appear light gray. The SiO_2 covered plates appear black. The shadow of the structure to the background is visible through the glass substrate.

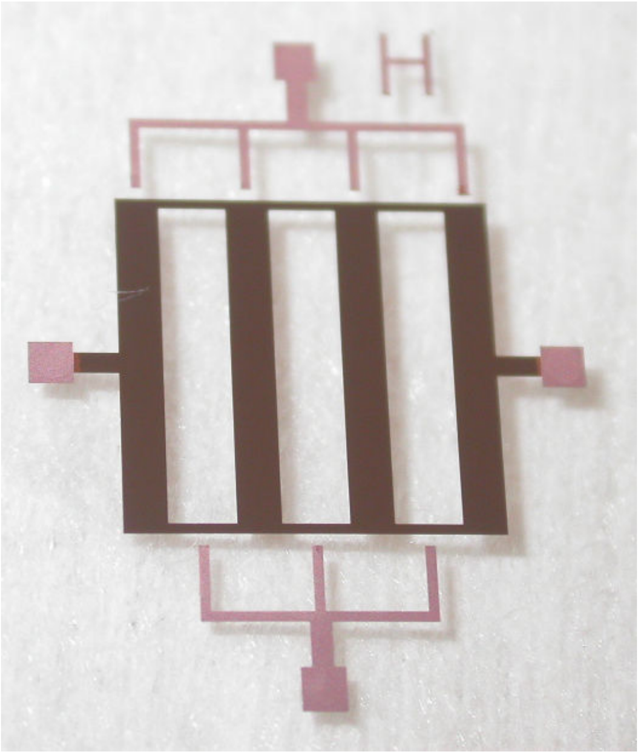

Fig. 4: Optical Image of a fabricated harvesting device (10 x 10 mm). The rolling mass is not shown in this picture.

V. CHARACTERIZATION

The fabricated devices were tested by applying an input voltage of 20 V and measuring the output voltage, while the steel rod was rolling over the SiO_2 covered plates. To measure the short output voltage spikes, an operational amplifier circuit was used with feedback and gain –0.1. The output of the measuring circuit was connected to an oscilloscope through a ×10 probe.

A typical series of output pulses is shown in Fig. 5. The pulses do not appear in equal time intervals, due to the rather random motion of the rod. This motion was chosen to approximate the behavior of a realistic body motion source.

Typically, the output pulses vary in height, and in most cases they appear to be lower than the input voltage. This indicates charge losses during the rod motion on the sputtered SiO_2, and during the detection of the pulse. Consequently most of the energy extracted from the rod motion is being lost. Improvement of the SiO_2 quality, increase of the rod-to-plate capacitance and increase of the input impedance of the measuring circuit are being investigated to enhance the performance of the device.

The discharging time was found to be relatively stable for all observed pulses, giving a time constant of around RC = 20 μs. Taking into account that the capacitance between the rod and the plates is expected to be of the order of 1 pF at the discharge point, and the input resistance of the measuring circuit is 10 MΩ, a discharging time constant of 10 μs is expected, i.e. reasonably close to what is measured.

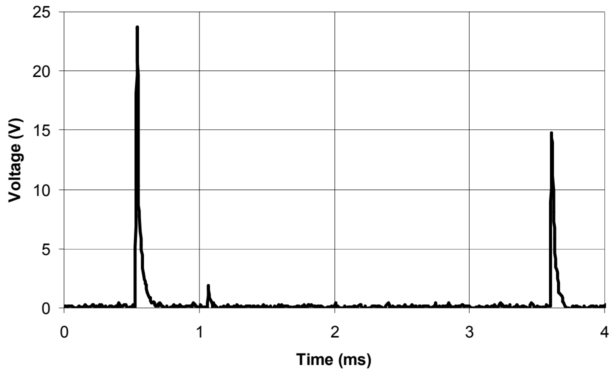

Fig. 5: Typical output voltage pulses of the generator, for an input voltage of 20 V.

The first pulse in Fig. 5 is plotted in more detail in Fig. 6. The amplitude of the pulse is higher than the input voltage, indicating power transduction from the kinetic energy of the rod in this case. The peak of the output pulse is 23.5 V, corresponding to a voltage gain of 1.18. The actual peak value of the output is expected to be higher than measured, due to some rapid charge transfer into the input capacitance of the measurement circuit.

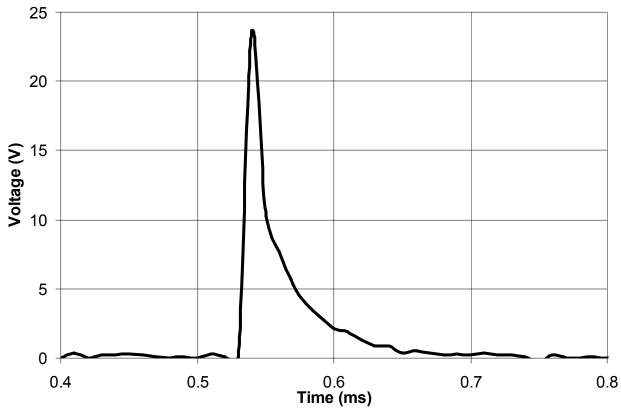

Fig. 6: Detailed plot of the higher pulse from Fig. 5. An amplitude of 23.5 V and discharging with time constant RC = 20 μs is observed.

VI. CONCLUSIONS

The potential advantages of this device compared to previous energy harvesters have been outlined above. The form of the output power, however, is the same as in previous constant charge electrostatic devices, namely high voltage pulses. The magnitude of these pulses can be reduced by lowering the priming voltage; however, this will also reduce the transduction force, which must be compensated by increasing the peak capacitance to maintain maximum power transfer.

Converting such high voltage pulses containing very small amounts of charge into a more useful form, without dissipating most of the energy they contain, is highly challenging. Although converter circuit designs have been developed [6], these have not yet been demonstrated in the monolithic form likely to be required to reach the necessary performance. Meanwhile, it is useful to consider alternative architectures to exploit the harvested energy in a body sensor application. One possibility is illustrated in Fig. 7. This is based around a potentiometric biosensor, such as those described in [7]. These produce a direct voltage output which varies in amplitude according to the measurand (in this case pH), but with a high output impedance so that virtually no power can be extracted directly.

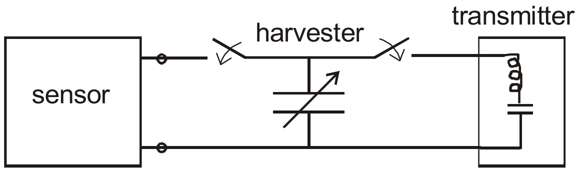

Fig. 7: Proposed architecture for self-powered wireless biosensor.

In the proposed architecture, the potentiometric source is used to provide the priming voltage for the electrostatic energy harvester. This then produces magnified pulses of an amplitude proportional to the sensor output. These pulses have sufficient energy to be discharged into the input of a simple resonant transmitter circuit, in which a loop antenna acts as the frequency defining inductor in the manner described in [8]. Consequently, short bursts at the transmitter resonant frequency are radiated whose amplitude is proportional to the measured parameter. These can be detected at a central module for further signal processing.

In conclusion, a novel non-resonant, external proof mass energy harvester is described which is suitable for body motion excitation, and its use in a self-powered wireless biosensor is discussed.

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