ELECTROSTATIC ENERGY HARVESTER WITH EXTERNAL PROOF MASS

M. E. Kiziroglou, C. He and E.M. Yeatman
Department of Electrical & Electronic Engineering, Imperial College London, UK

Abstract: In this paper a new electrostatic energy harvesting device is proposed. An external proof mass is used to overcome limitations of monolithically integrated devices. Simulations reveal the necessary geometry for constant electrostatic force. The electrical operation of the rolling mass is demonstrated and successful charging is achieved. It is found that a key requirement for effective energy harvesting in this device is the limitation of parasitic capacitance.

Key Words: MEMS, energy harvesting, power scavenging, electrostatic

1. INTRODUCTION

Extracting energy from ambient motion is an attractive way to avoid battery recharging or replacement in low power portable electronics. A wide range of motion scavenging devices have been reported [1,2]; 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.

We have previously reported silicon MEMS devices having an integrated mass forming one element of a variable capacitor, with power derived from an electrostatic force between moving mass and frame [3]. However, increasing the output power of such devices is a key requirement for applicability, and it has been shown that the maximum achievable power scales with the proof mass m [4]. In a monolithically integrated device, achievable mass is limited both by the substrate thickness and the low density of silicon. Also, the need for a through-wafer etch to maximize the mass adds to expense, and reduces process compatibility, e.g. for circuit integration. Implementing the proof mass as a separate object whose motion is constrained by the device packaged is therefore attractive.

Previously, Berthelot et al. demonstrated a device in which a free-rolling spherical proof mass generates power by colliding with a piezoelectric bimorph [5]. In this paper we describe for the first time a novel electrostatic energy harvester using a rolling cylindrical proof mass. All components are integrated with standard surface processing, with the exception of the proof mass.

2. OPERATING PRINCIPLE

The operating principle is illustrated in Figs. 1 and 2. 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.

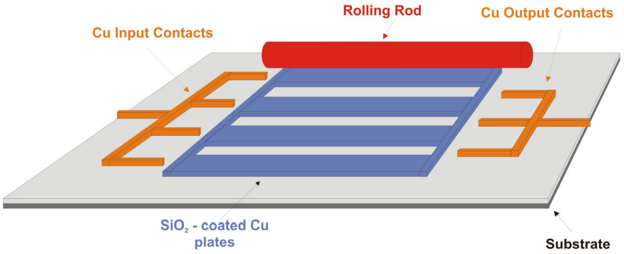

Fig. 1: Schematic illustrating operating principle

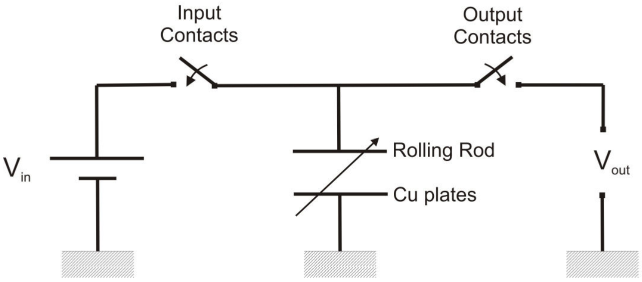

Fig. 2: Schematic circuit showing electrical operation

When the cylinder is aligned with one of the strip electrodes, it makes direct connection 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 between the cylinder and the strip electrode then

Proc. PowerMEMS 2007, Nov. 28-29, 2007, Freiburg, Germany, pp. 117-120.

increases, with the cylinder at constant charge, so that as the capacitance between cylinder and electrode 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.

This operation is equivalent to that of the monolithic device of [2], but has several key advantages: the mass can be significantly greater for an equivalent device size; no suspension structure is needed; the travel range (to which the achievable power is also proportional) is greatly increased, partly because of the elimination of the flexural suspension; and the output is provided in several pulses per motion cycle, rather than a single one. The latter characteristic is valuable because parasitic capacitances make it difficult to benefit from a large motion range in a single pulse system, and the reduction of the output pulse amplitudes makes implementation of the power regulation circuit less challenging.

3 DESIGN AND SIMULATION

3.1 Basic Design

Obtaining high energy per travel segment depends on maintaining a high electrostatic force, which in turn depends on the variation of capacitance with cylinder displacement. The rolling electrode will initially receive a priming charge $Q = C_i V_{in}$, where C_i and V_i are the initial capacitance and priming voltage respectively. Although the extracted energy ΔU depends in principle only on C_i, V_{in} and the final capacitance C_f, the rate of variation of C is important because it determines the force variation. Peaks in the lateral force F may exceed the effective driving force and stall the motion, therefore a uniform force is optimal. Since $F = dU/dx$ and $U = Q^2/2C$, we can obtain:

$$F = \frac{1}{2} Q^2 \cdot \frac{1}{C^2} \cdot \frac{dC}{dx} \qquad (1)$$

For the rectangular strip electrodes of Fig. 1, the field and potential distribution was modeled using Ansys to obtain the capacitance variation vs. lateral position (Fig. 3), and from these results the force variation was calculated (Fig. 4). The results indicate that a reasonably uniform force is obtained.

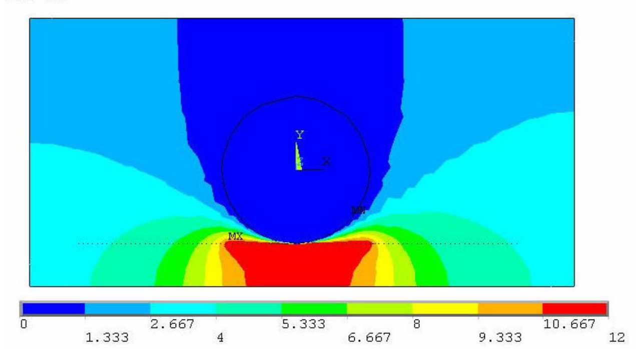

Fig. 3: Example of potential contours modeled in Ansys

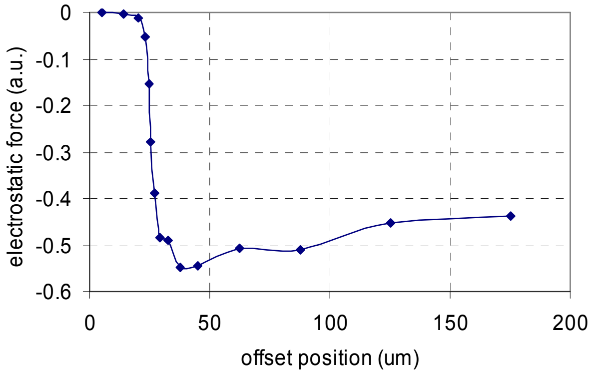

Fig. 4: Variation of electrostatic force with proof mass offset, modelled as $(dC/dx)/C^2$

3.2 Optimizing the Electrode Geometry

The travel range in Fig. 4 is limited, and the performance is easily altered by parasitic capacitance. For this reason we have considered alternative geometries; in particular, lateral tapering of the electrode width, to give a gradually decreasing overlap area. According to (1), a function C(x) is required for which $(dC/dx)/C^2$ is constant. A simple example is $C(x) = K/x$ for $x>x_o$, giving $F = 1/K$.

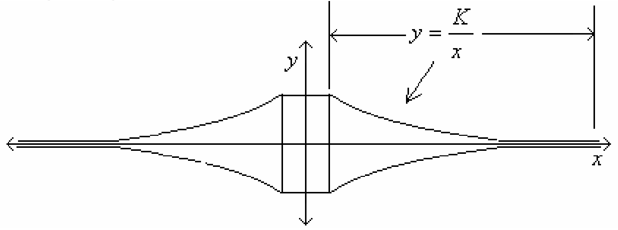

Fig. 5: Plate geometry for constant electrostatic force on displacing rod

If the rate of taper is slow compared to the rolling electrode width, then this will be reasonably approximated by an electrode width varying as

1/x. Such a form is illustrated in Fig. 5. For the tapered section, the constant force requirement is closely approximated. Furthermore, the design can be adapted to any travel segment distance by adjusting the taper rate. Note that the optimal taper will also be constrained by the need to keep the minimum capacitance (at the discharge position) above the background parasitics.

3.3 Conformal plates

One limitation of the current design, with a cylinder rolling on flat plate, is the relatively low value of initial capacitance. Maximising C_i reduces the priming voltage needed to achieve a certain force level, the priming energy, and the effect of parasitic capacitances. This capacitance limitation results from the cylinder having only a line of contact with the dielectric. In order to overcome this problem, we have also considered a design in which the fixed electrode and its overlaying dielectric layer are flexible, and can conform to the cylinder over a substantial area. This is illustrated in Fig. 6, for a cylinder resting on a flexible rectangular diaphragm.

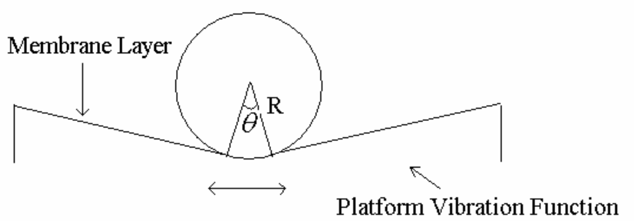

Fig. 6: Cylinder resting on a conformal diaphragm, comprising a thin dielectric with the fixed patterned electrode on its lower surface

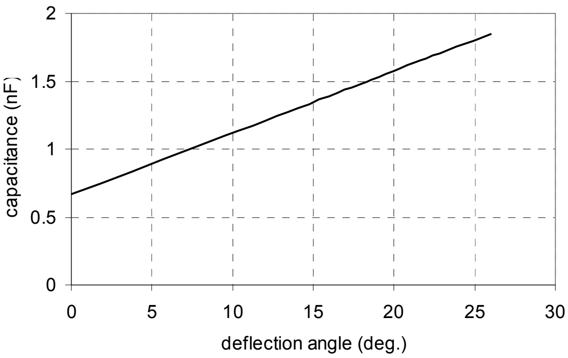

Fig. 7: Peak capacitance per unit cylinder length vs deflection angle θ

Peak capacitance of this structure was also modeled using Ansys, as a function of the deflection angle θ as shown in Fig. 6. The results (Fig. 7) indicate that a deflection of about 15 degrees is needed to double the capacitance, for a cylinder diameter of 1.5 mm and a dielectric thickness of 10 µm.

4. FABRICATION

The process flow used for the fabrication of the prototype device is shown in Fig. 8. A 100 mm diameter, 450 µm thick Si wafer was used as starting material. One µm SiO_2 was thermally grown and 200 nm Cu was sputtered on top using Ti as a thin adhesion layer. Photoresist patterns corresponding to the contacts were defined by conventional lithography and a thin Cu layer was electrodeposited through them (step 3 in Fig. 8).

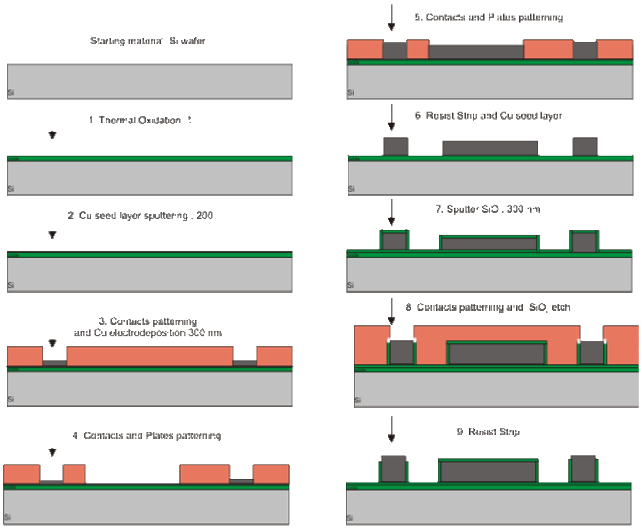

Fig. 8: Fabrication process flow for the electrostatic energy harvester

Another photolithography step followed, defining patterns for both the contacts and the plates of the device. Then, a 5 µm Cu layer was electrodeposited through the patterns. This two-step Cu electro-deposition was used to obtain a thicker layer for the contacts, thus allowing space for the deposition of dielectric over the plates. Subsequently, the resist was stripped and 300 nm SiO_2 was sputtered and etched at the contacts (steps 7, 8 and 9). The external mass used was a steel rod with diameter 1.5 mm. An optical image of the device including the external proof mask is shown in Fig. 9.

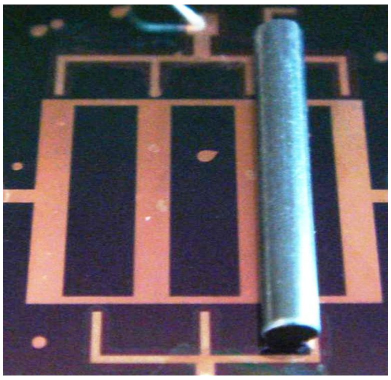

Fig. 9: Photograph of device with steel proof mass. Overall dimensions are ≈ 10 x 10 mm.

5. CHARACTERISATION

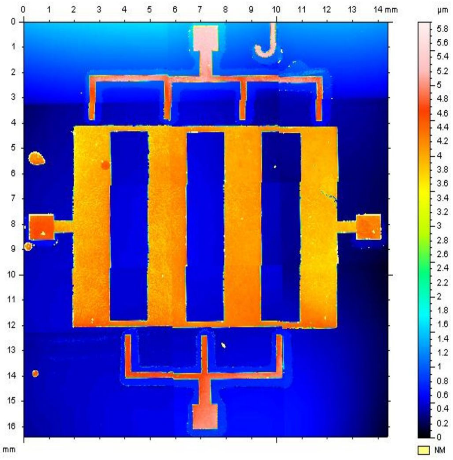

Fig. 10: Surface height map obtained by optical profilometry

Fig. 10 shows a surface profile of a fabricated device, illustrating the uniformity and height matching of the charge and pre-charge contacts and the main strip electrodes. All electrodes are fabricated by electroplating copper into photoresist molds, and the dielectric layer is sputtered SiO_2. Initial tests show that the moving roller makes effective electrical contact with the charge and precharge electrodes during travel (Fig. 11). To detect and store the output pulses of the device, a suitable circuit should be developed with a high input resistance and low parasitic capacitance [6].

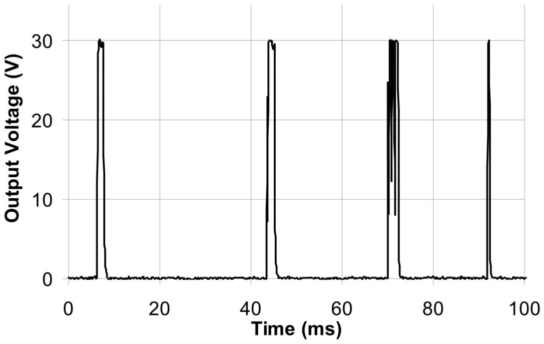

Fig. 11: Measured pulses indicating contact of moving roller to opposing pairs of charging electrodes.

6. CONCLUSION AND FURTHER WORK

A novel electrostatic energy scavenging generator has been proposed and analysed. Design variations were considered towards the optimisation of the generation efficiency. Prototype devices were fabricated and charging operation was demonstrated. It was found that suppression of parasitic capacitance to the silicon substrate is critical for successful energy generation. Consequently, improved devices using glass substrates are currently under fabrication.

REFERENCES

[1] J. A. Paradiso and T. Starner, "Energy scavenging for mobile and wireless electronics," *Pervasive Computing, IEEE*, vol. 4, pp. 18-27, 2005.

[2] S P Beeby, M J Tudor and N M White, “Energy harvesting vibration sources for microsystems applications”, Meas. Sci. Technol. Vol. 17, pp R175-R195, 2006.

[3] P. Miao, P. D. Mitcheson, A. S. Holmes, E. M. Yeatman, T. C. Green, and B. H. Stark, "MEMS inertial power generators for biomedical applications," *Microsystem Tech.*, vol. 12, pp. 1079-1083, 2006.

[4] P. D. Mitcheson, T. C. Green, E. M. Yeatman, and A. S. Holmes, “Architectures for vibration-driven micropower generators,” *J. Microelectromechanical Systems*, vol. 13, pp. 429-440, 2004.

[5] B. Cavallier, P. Berthelot, H. Nouira, E. Foltête, L. Hirsinger and S. Ballandras, “Energy harvesting using vibrating structures excited by shock”, Proc. 2005 IEEE Ultrasonics Symposium, pp. 943-945, 2005.

[6] P. D. Mitcheson, T. C. Green and E. M. Yeatman, “Power processing circuits for electromagnetic, electrostatic and piezoelectric inertial energy scavengers.” *Microsystem Technologies*, 2007, Vol: 13, Pages: 1629 – 1635.