Flexible substrate electrostatic energy harvester

M.E. Kiziroglou, C. He and E.M. Yeatman

Energy harvesting is attractive for powering wireless sensors, especially in applications such as body sensor networks and pervasive sensing, where power source replacement or recharging is impractical. A MEMS (micro-electro-mechanical systems) electrostatic harvesting device suitable for body motion has been reported previously, using a rolling rod as the proof mass. A new rolling rod device is presented, employing a flexible substrate to allow the formation of a concave structure. Suitable rod confinement and increased rod–plate capacitance are achieved. Regular power transduction even under impulse motion excitation is reported, supplying 0.5 μW of output power.

Introduction: Energy harvesting is the main alternative to cable delivered power and batteries for applications where access to devices is either impractical or impossible. Such applications include body implanted devices, oceanographic measurements and pervasive sensing. Motion, light and heat are all potential power sources for harvesting.

In the human body, light and temperature gradients are limited, leaving motion as the main power source. In addition, the human motion has a wide, low-frequency spectrum (typically in the range 1–10 Hz), making resonant devices, including most piezoelectric cantilever-based harvesters, unsuitable for optimum transduction. Furthermore, implantation requires device size of a few millimetres or less, which is not favourable for electromagnetic transduction. On the other hand, scaling laws for electrostatic transducers make them well suited to such small dimensions.

A MEMS (micro-electro-mechanical systems) electrostatic harvesting device, based on appropriately timed charging and discharging of a capacitor with the moving proof mass forming one of the plates, has been previously developed, providing energy of 150 nJ per cycle [1]. By use of intermittent motion between proof mass positions, this device operates non-resonantly, and thus has a broadband response. However, the use of monolithic silicon limits the achievable mass, and the restricted geometry and necessarily soft suspension result in excessive motion in unwanted axial directions. A device concept that overcomes these limitations, employing an external, free rolling rod as the proof mass, has been proposed recently [2].

An implementation of such a device is shown in Fig. 1*a*. A steel rod can roll over an array of dielectric-coated Cu plates. The capacitance (C) formed between the plates and the rod changes periodically with rod displacement following the plate geometry. Charging at maximum C is achieved by providing a priming voltage through side contacts (top of Fig. 1*a*). External acceleration can make the rod move with respect to the substrate owing to its inertia and C is reduced. This reduction occurs at constant charge (Q) and the rod–plate voltage is increased according to $V = Q/C$. The additional energy stored in the capacitor corresponds to the work done against the attractive electrostatic force between the rod and the plate. This energy is extracted by discharge at minimum capacitance through side contacts (bottom of Fig. 1*a*).

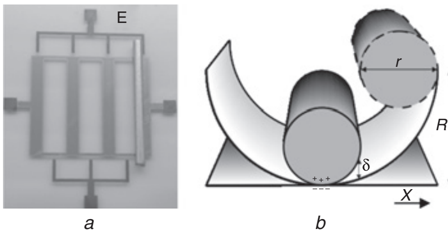

Fig. 1 *Optical top view of planar electrostatic harvester fabricated on glass, and schematic of interface between two cylindrical surfaces*

a Optical top view of harvester
b Schematic of interface

Key advantages of this device concept are the larger proof mass, the lack of a suspension system and the ability to provide power in a series of pulses rather than in one large voltage pulse per transit direction. In the implementation presented in [2] (Fig. 1*a*), the capacitance values remains under 10 pF even for dielectric thickness below 100 nm, leading to low output power (12 nJ per cycle for a 2.4 voltage gain between charge and discharge). This is difficult to improve on owing to the fundamentally small achievable contact area between planar and cylindrical surfaces.

To address this limitation, a new, concave substrate electrostatic harvester architecture is introduced here. A suitable microfabrication method is developed and a first device prototype is presented demonstrating performance improvement over the planar electrostatic harvester.

New device concepts: A schematic of a rod placed in a semi-cylindrical surface is shown in Fig. 1*b*. The metal rod can roll inside the fixed concave substrate which includes the dielectric covered plates and the input and output contacts. The capacitance between the metal rod and a substrate plate will depend on their relative curvature. Higher substrate curvature results in larger maximum and minimum rod to plate capacitance and hence in higher power transduction. The largest achievable capacitance corresponds to the extreme case of the rod being wrapped by the substrate and can be calculated in good approximation analytically as a parallel plate capacitor. Assuming a 10 mm-long rod with a diameter of 1.5 mm, a roughness induced airgap of 1 μm between rod and plate and a plate width of 1 mm, a capacitance value of around 90 pF is obtained. This is about ten times larger than corresponding simulation results for the planar substrate geometry. Hence, a tenfold increase of output power is predicted for this case. Further power increase can be expected if it is taken into account that pico farad level parasitic capacitances suppress the power gain of planar electrostatic harvesters.

Another unique characteristic of the proposed device architecture is the natural confinement of the rod inside the concave substrate. This results in additional advantages of the proposed structure. First, it makes the device more compact, improving handling and potentially simplifying the packaging process. In addition, it allows rod oscillation in the concave substrate. Any energy that is not transformed to electric discharge pulses during a rod transit from one side to the other is not lost in collisions at device walls. Instead, it is transformed to electrostatic and gravitational energy and can be exploited in subsequent rod oscillations. This intermediate energy storage allows regular pulse generation even in the case of impulse motion excitations, to the benefit of efficiency and power handling simplicity, although the associated resonant characteristic does alter the spectral response.

Fabrication method: The process developed to fabricate the concave substrate structure is illustrated in Fig. 2*a*. A polyimide sheet is used as the substrate to allow flexibility. An appropriately cut polyimide sheet is mounted on a 100 mm glass wafer for compatibility with conventional micromachining. The plates, dielectric and contacts can then be deposited on the substrate using the plain wafer technique described in [2]. The film is released from the wafer and individual bendable device substrates are obtained by film cutting. The substrates are rolled and fixed to the appropriate curvature individually using a sticking film. Device wiring is performed by drilling vias through the polyimide and subsequent filling with conducting paint. Finally, an external rod is placed in the device through the sides. Optical images of a substrate before and after rolling are shown in Figs. 2*b* and *c*, respectively. In Fig. 2*b*, a 2.5 mm-diameter steel rod is also shown. The drilled and filled vias for electrical access to the plates are visible in both images.

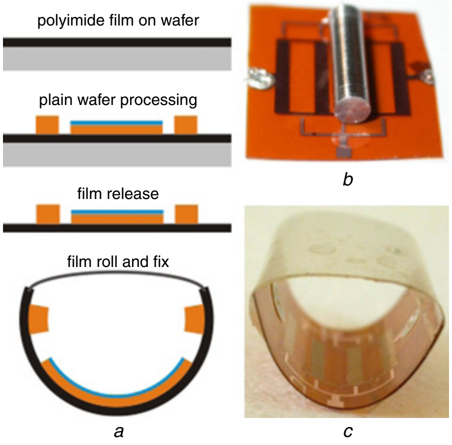

Fig. 2 *Fabrication and optical images*

Results and discussion: A first prototype of the proposed architecture was characterised, with plate size 1 × 10 mm and SiO_2 dielectric thickness of 50 nm. A 10 mm-long, 2.5 mm-diameter steel rod was used, of mass 0.4 g. Rod–plate capacitance measurements were performed while the rod rolled on a flat polyimide substrate (Fig. 2*b*). The results are plotted against rod displacement for rolling over a single plate in Fig. 3*a*. A minimum capacitance of 2 pF and a maximum of 9 pF is observed, 50% higher than the values obtained on stiff substrates by the same measuring technique [3]. This increase can be attributed to local substrate bending caused by the rod. Capacitance against displacement measurements are difficult to obtain on a rolled substrate without disturbing the rod to substrate contact, but static capacitance sampling for different substrate curvatures has revealed an increase to values over 15 pF.

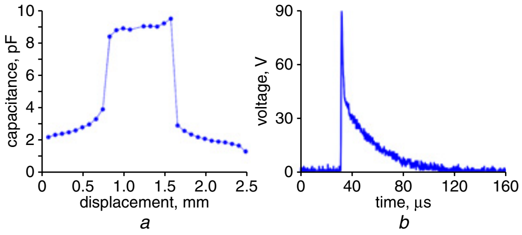

Fig. 3 *Capacitance against displacement for 2.5 mm-diameter rod rolling on flat polyimide device substrate, and typical output pulse of device illustrated in Fig. 2c, with 30 V priming*

a Capacitance against displacement
b Typical output pulse

Power generation experiments were performed on the low curvature device illustrated in Fig. 2*c*, using a range of priming voltages from 1 to 30 V. Steady pulse generation was observed, capable of maintaining a pulse plot on the oscilloscope, even for impulse motion excitation. This was made possible by rod oscillation in the concave substrate, as discussed earlier. A typical output pulse measured through an opamp buffering stage with input resistance 10 MΩ [2] is shown in Fig. 3*b*. This pulse corresponds to a priming voltage of 30 V. The voltage gain is 3. This gain value is regularly obtained throughout the priming range. The energy of the pulse in Fig. 3*b* is 8.1 nJ if an output capacitance of 2 pF is assumed, as measured flat. Accounting for the six output pulses generated per cycle, this corresponds to 0.05 µJ per cycle. The device geometry corresponds to a rod oscillation frequency at 10 Hz, if no friction and a small oscillation angle are assumed. This calculation is consistent with observation of the rod motion during operation. The corresponding power generation is 0.5 µW. Continuous operation at this power level for a few seconds after every impulse excitation was typically observed. If capacitance increase due to bending is taken into account, a higher energy per pulse is obtained.

Conclusions: A novel electrostatic energy harvester architecture is introduced, using a flexible material as the device substrate. A new, reliable fabrication method with notable simplicity has been developed. The main advantages of this new architecture are the capability for high input and output capacitance, improved device compactness and consistent operation even under irregular motion excitation. The results demonstrate power generation at 0.5 µW, approaching the requirements of low power electronics. Further improvements of the device may include scaling to implantable device sizes and the use of highly straight and smooth metal rods to increase capacitance and, therefore, power generation.

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One or more of the Figures in this Letter are available in colour online.

M.E. Kiziroglou, C. He and E.M. Yeatman (*Department of Electrical and Electronic Engineering, Imperial College London, London, SW7 2AZ, United Kingdom*)

E-mail: m.kiziroglou@ic.ac.uk

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