

Micro-Machined Variable Capacitors for Power Generation

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ABSTRACT

Variable capacitors are key elements in electrostatic micro-power generators. In such devices inertial forces are used to do work against the electric field of the capacitor, thereby converting mechanical energy to electrical potential energy that can be extracted by a suitable circuit. Applications are envisaged in portable, wearable or implantable electronic devices where body motion could provide the mechanical energy source. This paper describes the fabrication and initial testing of a micro-machined variable capacitor for power generation, with overall dimensions in the meso-scale. The measured capacitance of the device varies from 100 pF to around 1pF as the mass moves from initial to final position, corresponding to a hundred-fold increase in voltage if the device is operated in constant charge mode. Initial tests of the capacitor on a vibration system (10Hz) have shown that a periodic high voltage output of 2.3 kV can be generated if the capacitor is charged by a voltage source of 26 V. This corresponds to an energy conversion rate of 2.4 μ J per cycle, or 24 μ W at a vibration frequency of 10Hz.

INTRODUCTION

Most micro-electro-mechanical systems (MEMS) today utilise macroscopic power sources. This places some limits on the applications of MEMS devices. For example, in some potential applications, these micro-machined devices have to be completely embedded or fabricated in the structures where external power is not accessible. Miniaturized implantable medical sensors are one of these applications. Although high-energy batteries are currently used to power these devices, this solution is less than satisfactory. Batteries are normally bulky and contain a finite amount of energy, their shelf life is limited and the chemicals contained in the batteries may be toxic. In search for an alternative power supply for these applications, micro-machined power generators are promising, being of a scale which can be easily integrated into these MEMS devices. Some of them can be specially designed to convert ambient energy in the environment into electrical power. Thus these MEMS devices will become self-powered.

Although miniaturized self-contained power supplies are not a new idea, they have not attracted much attention until recently. Attempts have been made to design and fabricate micro-machined power generators utilising thermal energy [1-4], kinetic energy of gas flow [5] and mechanical energy converted by a piezoelectric element [6] or a permanent magnet [7-9].

We have designed and fabricated a micro-machined mechanical-electrostatic power generator. Such an approach was chosen because our particular interest lies in the possible applications in wearable, carried and medical implant electronics. In these applications, photo-electric energy is normally not available. Although living bodies contain thermal energy, the extraction possibilities for a micro-scale device are limited, as the thermal gradients within the body are small, and thermal extraction depends on temperature difference across the device. Kinetic energy from the volume flow of fluids requires a comparatively high reservoir fluid

pressure, and more crucially, require the device to present an obstruction to the fluid flow, with obvious safety implications. As for the transduction mechanism, piezoelectric transducers will suffer from self-discharge at the low frequencies of these applications, while electromagnetic designs cannot achieve high damping forces for low speed motion. Also, both piezoelectric and electromagnetic transducers are relatively complicated to fabricate, particularly at dimensions compatible with body implantation. The electrostatic transducer is simple in structure, being basically a variable capacitor formed between two metallic electrodes separated by a dielectric. Tashiro *et al* [10] reported an electrostatic power generator that harnesses the motion of a living body. A honey-comb-type variable capacitor with a capacitance variation of 32 – 200 nF was used to convert mechanical energy into electrical energy. An output of 58 μW was reported to be generated with a constant charging voltage of 24 V and a load of 1.0 M Ω . However this device is relatively large, at a mass of 0.64 kg.

The key element of an electrostatic micro-machined power generator is a variable capacitor, which can convert mechanical energy into electrical energy by means of the work done by an external force against the electric field formed between the capacitor plates. This paper will present the structure and the results of initial test of such a micro-machined variable capacitor. Although the external circuit for power extraction from the capacitor is still under development, the operational principle of the power generator is also discussed.

DEVICE STRUCTURE AND OPERATIONAL PRINCIPLE

The initial prototype was fabricated using MEMS techniques, with overall dimensions at a “meso-scale” between conventional engineering and micro-scale; its cross-section is shown schematically in Figure 1. A gold proof mass of 4.3 g, supported on a highly flexible polyimide membrane, is suspended between a silicon top plate and a quartz base-plate. The very low mechanical Q prevents accurate measurement of the resonance frequency, but we estimate it at 10 – 20 Hz. Patterned metal films on the base-plate and the membrane form the fixed and moving plates of the capacitor, the latter being connected to an external circuit only at the extremes of its travel where it makes contact with plated contact studs.

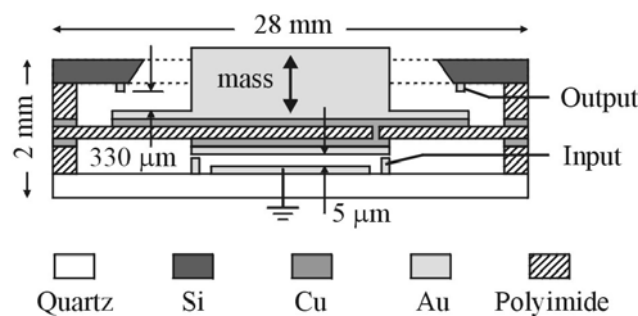


Figure 1 Cross-section of the variable capacitor.

Power generation is achieved in this device by pulling apart the base plate and the movable plate and then extracting energy stored in the electric field. During the input phase, the mass is forced against the contact studs on the base plate, connecting it to a charging circuit that brings it to a starting potential. In response to motion of the frame, which is attached to the moving “host” (e.g. person), the mass is accelerated sufficiently in the opposite direction and moved to the top plate where it is stopped by the contact studs on the top plate. The energy stored in the capacitor is then extracted. Figure 2 shows the essential elements of a basic

charging and extraction circuit. During the input phase, transistor Q1 is turned on to transfer energy from the source B1 into the inductor L1. When Q1 is switched off, this energy is transferred to the variable capacitor C1 through a half-cycle quasi-resonant action between L1 and C1. During the output phase, the charge is recovered from the variable capacitor, at a higher voltage, by a second quasi-resonant action, this time between C1 and L2. This action transfers energy from C1 to L2, and then from L2 back into B1. The pre-charge operation is initiated by the control circuit while the moving plate is in contact with the Input terminal, with the charge delivered being governed by the Q1 on-time as set by the control circuit. The extraction operation occurs automatically when the moving plate makes contact with the Output terminal.

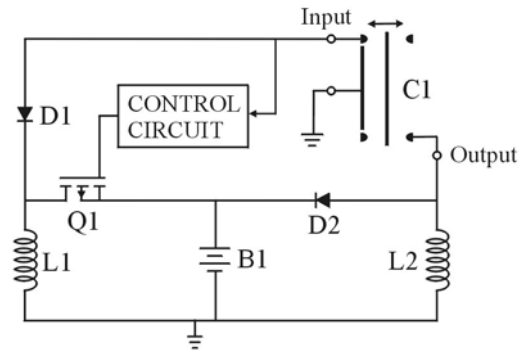


Figure 2 Simplified schematic of the proposed charging and extraction circuit.

RESULTS AND DISCUSSION

The capacitance measurement of the device was conducted using a PM 6303 RCL meter. The device was mounted on a fixed stage. The movable plate of the device was attached to a micrometer which moves the plate with a resolution of 10 μm . Capacitance was measured between the movable plate and the base plate, as a function of the separation of these plates. The result is shown in Figure 3.

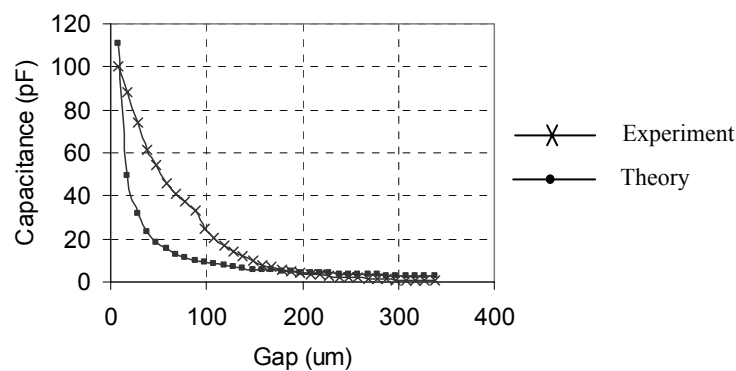


Figure 3 Variation of capacitance throughout the travel distance of the movable plate.

It can be seen that the measured capacitance (crosses) of the device varies from $C_1 = 100$ pF to around $C_2 = 1$ pF as the mass moves from bottom to top, corresponding to a hundred-fold increase in voltage if the device is operated in constant charge mode. The measured capacitance decreases more slowly than that calculated from an air gap capacitor (dotted line). Adding fringing field effects to the model, for this plate area and separation, cannot account

for the substantial deviation seen; however, the measured results correspond well to the model if tilting of the moving plate during travel occurs.

A leakage measurement was also carried out. The capacitor was charged to an initial voltage V_0 at its minimum gap position (input phase) and then disconnected from the charging source. The movable plate was isolated from both charging source and top contact for different delay times t_D , while held at an intermediate capacitance C_m , and then moved up to its maximum gap position (output phase), and the output voltage recorded. The discharge transient amplitude is normalized to the zero delay discharge voltage and plotted against the delay time as shown in Figure 4. If we assume the device has a leakage path resistance R , then the discharge transient amplitude can be described by:

$$V_f = \frac{C_1}{C_2} V_0 e^{-\frac{t_D}{RC_m}}$$

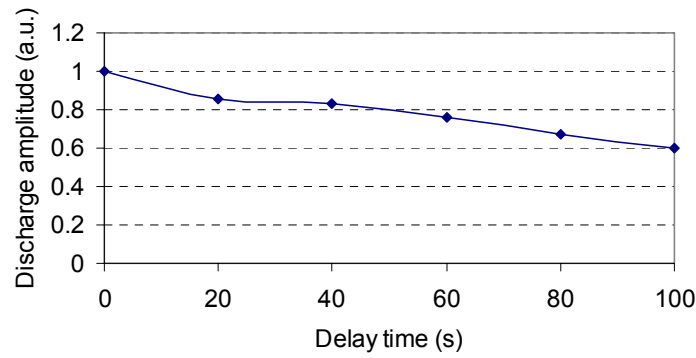


Figure 4 Reduction in the discharge transient amplitude against time.

Figure 4 indicates that the time constant for decay of the charge is about 200 s, indicating a leakage resistance above 1000 G Ω . This suggests that there will be negligible charge leakage when the device is in operation.

Initial discharge tests of the capacitor were conducted on a vibration system. The variable capacitor was pre-charged by a current-limited voltage source of 26V connected between the Input terminal and the Ground terminal, as shown in Figure 5. The device was clamped to a shaker table (IMV model PET-05A), the motion of which was measured in real time using a Solartron frictionless inductive displacement transducer. To observe the discharge, the Output terminal was fed into a virtual earth amplifier with in input resistance of 50 M Ω and a feedback resistor of 50 k Ω . The amplifier output, representing the capacitor output voltage scaled by a factor of $-1/1000$, was observed on an oscilloscope.

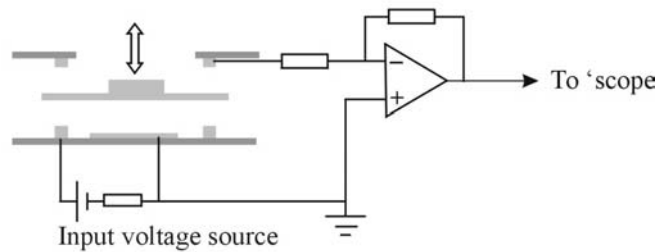


Figure 5 Experimental set-up for measuring periodic discharge, with the device mounted on a vibration testing system.

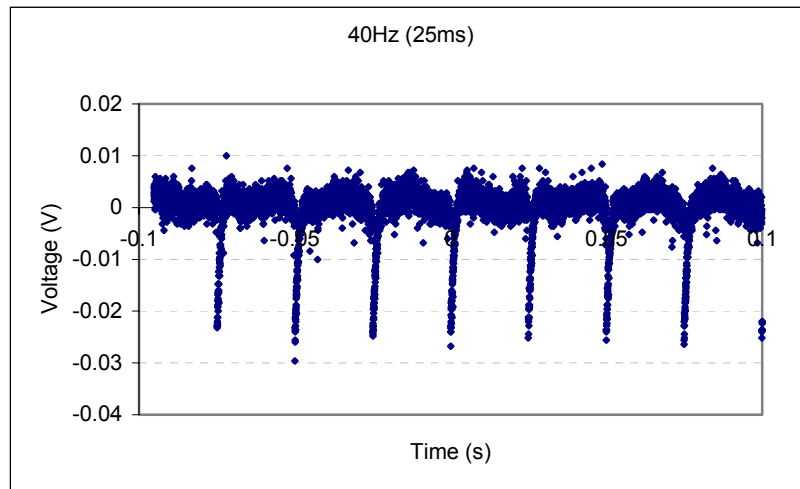


Figure 6 Periodic discharge voltage for 40 Hz operation.

In Figure 6, the periodic discharges generated from the device are seen. The time intervals of the periodic discharges correspond to the vibrating frequencies of the vibration system. The low, and variable, amplitude of the discharges seen in the figure result simply from the sampling rate being too low to catch the peaks for this multi-cycle measurement. The discharge test was carried out in the frequency range from 5 Hz to 100 Hz, and the device was shown to operate reliably across this range.

If the time scale is expanded, a complete discharge transient can be viewed. Figure 7 shows the discharge transient when the device is vibrating at 10Hz. The amplifier output is -2.3V, corresponding to a capacitor voltage of 2.3kV. Since the output of the charging source was set to 26V, this corresponds to an 88.5 fold increase in voltage, which is in reasonable agreement with the ratio of capacitance increase of 100. The difference may result from parasitic capacitances in the system. The energy stored in a capacitor is simply $\frac{1}{2}CV^2$, and the maximum energy generated from the device will be the difference between energies stored in the capacitors at minimum and maximum gap positions. In the present case this corresponds to an energy conversion rate of 2.4 μJ per cycle, or 24 μW at a vibration frequency of 10Hz.

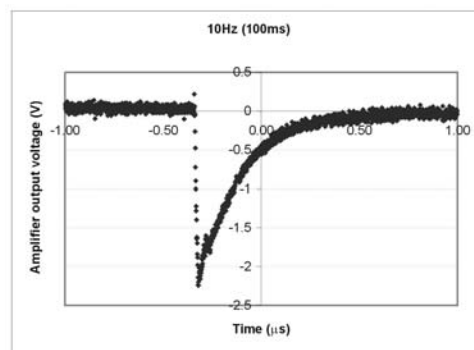


Figure 7 Discharge transient of one of the periodic discharges at 10Hz.

CONCLUSIONS AND FUTURE WORK

A prototype variable capacitor has been designed and fabricated. The capacitance measurement shows that the capacitance of the device varies from 100pF to around 1pF, corresponding to a 100-fold increase in voltage. The leakage test shows that the time constant is well over 100s, which is much longer than the working cycle of the device, indicating that charge leakage is negligible in operation. This is certainly necessary for the achievement of high efficiency in low frequency applications. Discharge tests on a vibration system proved that the device is operational in a wide frequency range and that a high output voltage can be generated from the device. Although the variable capacitor is the key element of the electrostatic power generator, a complete generator will require suitable power processing electronics. The design of such electronics has been outlined, and implementation is currently under way. The overall efficiency of the power generator will of course depend on the associated electronics as well as the electro-mechanical structure and operation. This will be determined by tests on a fully integrated generator. The existing generator is a hybrid integrated device; smaller, more highly integrated structures are planned to meet such applications as medical implants.

ACKNOWLEDGEMENTS

We are grateful to the Engineering and Physical Sciences Research Council, and to the European Commission (Disappearing Compute Initiative) for financial support of this work.

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