Electrostatic Swing Energy Harvester

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***Abstract*— Generation of the electric power by permanently polarized (electret containing) capacitor is analyzed and investigated in the matter of energy harvesting from oscillations and rotation. Experimentally demonstrated the generation of short high-voltage (up to 1 MV) pulses or low voltage (few volts) alternating current that can be rectified and stored.**

I. INTRODUCTION

Due to the spreading of mobile and autonomous devices, much interest has been attracted by energy scavenging from ambient sources such as vibrations and rotation. A good review of techniques to perform electromechanical energy conversion is presented in [1]. Besides inductive and piezoelectric converters, capacitive energy harvesters [2-5] are investigated due to the good capability of miniaturization, ability to work at very low frequencies, and can be used without external voltage bias if the electret is used [4,5].

The using of homopolar charge deposited to the surface of dielectric dates back to 1778 when Georg Christoph Lichtenberg demonstrated his famous figures [6], which is considered as an invention of a dry electrostatic printing process currently known as Xerox technology. Currently available materials, for example Teflon® AF from DuPont or CYTOP™ from Asahi Glass Co.(AGC), amorphous perfluoropolymers allow for the very high charge density [7], up to $8\cdot10^{-4}$ C/m^2, due to the structure of the polymer (density and deepness of the electron traps, and local defects such as chain breaks, double bonds, free radicals, etc.). Due to this, the electret equipped capacitive energy harvester approach became the attractive choice for miniature, micro-electro-mechanical or thin-film devices.

The heteropolar electret, which contains dipoles, i.e. displaced charges of both signs, produces the permanent electric displacement, ***D***. In this case the variation of capacitance between the electret and movable electrode, known as a Kelvin probe, generates the electric current or, if the source of electric field is not accessible, the variation of capacitance of two probes generates the current between them [8]. In contrast with heteropolar electret, the homopolar electret contains real charges of only one sign and charge of opposite sign is induced in available electrodes. The value of these charges depends on the capacitance between the electret charge and corresponding electrode that works as an electrostatic "mirror". If electret layer is deposited on the metalized substrate, the embedded capacitance between the charge and metallization is constant but capacitance between the charge and the movable electrode over the electret can be varied by number of ways: vibration, rotation or linear displacement. The conceptual equivalent electric circuit for such a device is presented in Fig. 1, where Q is the electret charge, Q_1 is the charge induced in the electret equipped, polarized electrode (metalized substrate) and Q_2 is the charge induced in the movable, passive electrode. Charges Q_1 and Q_2 have the sign opposite to the charge Q and $Q_1 + Q_2 = Q$.

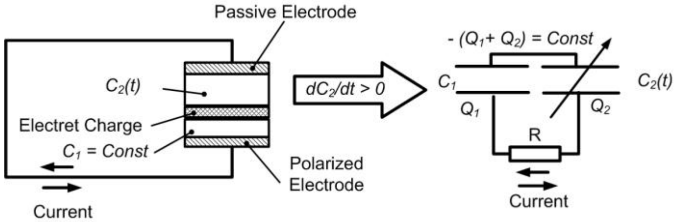


Fig. 1. Equivalent electric circuit of the electrostatic, electret polarized mechanoelectric converter. Variation of capacitance C_2 lead to the redistribution of charge, $Q_1 + Q_2 = Q$, induced by electret charge, $-Q$, between electrodes and alternating electric current flows through the load R.

Electret homopolar charge of density, σ, creates the electric field on both sides of charged layer while the total flux of electric displacement is limited by σ according with Gauss theorem [9], $D = \sigma/(2\varepsilon_0)$, where ε_0 is the dielectric permittivity of a vacuum. The resulting equilibrium charges can be defined from the condition of equal voltage on capacitors, $V = Q_1/C_1 = Q_2/C_2$, and constant sum of Q_1 and Q_2. For the varied capacitance, $C_2(t)$, the electric current flows between C_1 and C_2 is defined simply as

$$i(t) = \frac{dQ_1}{dt} = -\frac{dQ_2}{dt} = Q \cdot \frac{C_1}{(C_1 + C_2(t))^2} \cdot \frac{dC_1}{dt} . \quad (1)$$

Note that Eq. (1) accounts for any forces, including electrostatic ones, by means of the temporal function $C_1(t)$, which is defined by dynamics of movable, passive electrode (or electrostatic mill is applicable).

II. Model of Electrostatic Swing Energy Harvester

The simplest design for the electrostatic swing energy harvester is the linear displacement of conductive shield between the electret and passive electrode (see Fig. 2).

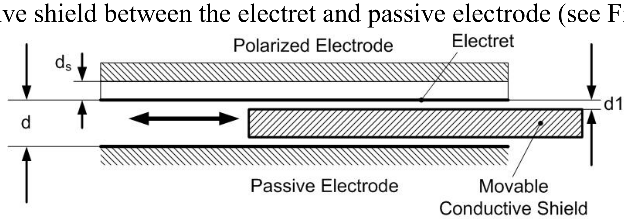
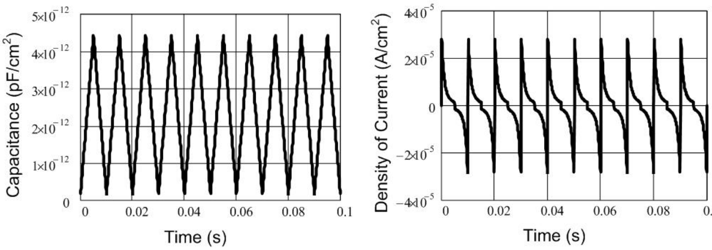


Fig. 2. Design of electrostatic energy harvester with conductive shield sliding between electrodes. Simulated variations of capacitance, C_2, in Eq.(1): (a) capacitance per 1 cm^2; (b) current density. Electret substrate thickness, $d_s = 100$ μm, gap between electrodes, d = 1 mm, gap between electrodes and shield, d1 << d.

The corresponding variation of capacitance, C_1, with frequency 100Hz is presented in Fig. 3(a). Numerical simulation according with Eq. (1) leads to the oscillating current that shown in Fig. 3(b).



(a) (b)

Fig. 3. Simulated variations of capacitance, C_2, in Eq.(1): (a) capacitance per 1 cm^2; (b) current density. Electret substrate thickness, 100 μm, gap between electrodes, 1 mm.

The variation of energy density stored in the capacitor $C_2(t)$, $E(t) = q_2^2/(2C_2(t))$, defines the available instant power, $W(t) = dE/dt$. The average available power during the period of oscillations, T, is $Wa = \frac{1}{T}\int_0^T W(t)dt$ that was simulated for varied gap between passive and polarized electrodes. Fig. 4 shows the variation of this parameter at three widths of gap between electrodes (1 mm, 5 mm and 10 mm) and the fixed gap between the shield and electrodes (100 μm) as a function of the substrate thickness.

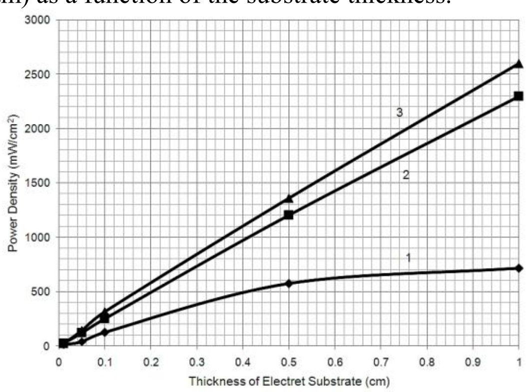
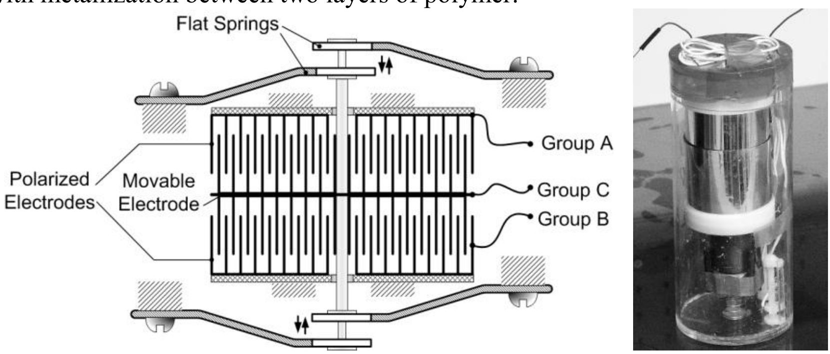


Fig. 4. Average available power density at the distance between electrodes: 1 – 1 mm, 2 – 5 mm and 3 – 10 mm.

The giant power available at the wide gap is not surprising due to the very wide variation of capacitance, $C_2(t)$. The challenge is to extract this power because the low average capacitance between electrodes is 100 fF (10^{-13} F), leads to the effective output impedance at 100 Hz equal to $1.6\cdot10^9$ Ohms. Therefore, there is the optimal thickness of substrate that allows to achieve the maximal extraction of the power.

III. EXPERIMENTAL RESULTS

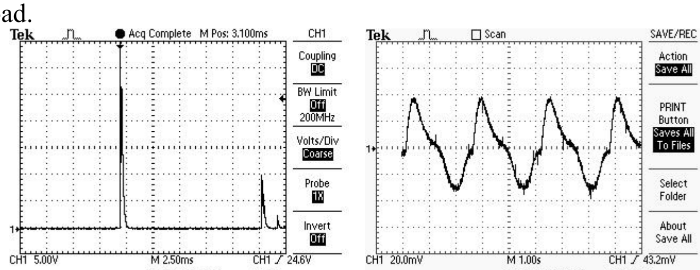
The prototype of electrostatic energy harvester with axial displacement of spiral electrodes is shown in Fig. 5. The electret is fabricated by the deposition of Teflon® AF (a copolymer of polytetrafluoroethylene (PTFE) and dioxole Poly[4,5-difluoro-2,2-bis(trifluoromethyl)-1,3 dioxole-co-tetrafluoroethyene]) on the bimorph Polyester substrate with metallization between two layers of polymer.



(a) (b)

Fig. 5. The electrostatic energy harvester with axial displacement of spiral electrodes. (a) Scheme of device. The polarized electrode (C) oscillates between 2 passive electrodes (A and B). Separate rectification is required due to the opposite phase of currents. (b) Tested prototype. Diameter of device – 50 mm.

Polarized electrode spiral axially moves between two housing spirals of passive electrodes that generates currents between terminals AC and BC. Because these currents alternate in the opposite phase, they should be rectified separately before collection of charge in the buffering capacitor. If terminals (A, B and C) are disconnected during the displacement of polarized electrode, the significant voltage is created between electrodes A and C as well between B and C due to the non-equilibrium distribution of charge. Fig. 6(a) shows the typical discharge of this voltage through the 200 MOhm resistive divider 2000:1 while Fig. 6(b) illustrates the current through the permanently attached 1 MOhm load.



(a) (b)

Fig. 6. The typical discharge of electrostatic energy harvester with spiral electrodes: (a) through the 200 MOhm load in the moment of full displacement. The second, small peak is residual discharge due to the vibration of switch; (b) oscillating voltage on the 1 MOhm load at the low frequency (0.5 Hz) oscillations of the polarized electrode.

When electrodes connected to the rectifier (see Figure 7), the displaced charge is accumulated on the buffering capacitor, 10 nF. To decrease the discharge of capacitor through the oscilloscope, the additional resistor, 49 MOhm, is installed in serials with oscilloscope input (1 Mohm). Leakage current through this load, 50 MOhm, increases with voltage on the capacitor and saturates when supplied and consumed currents are balanced.

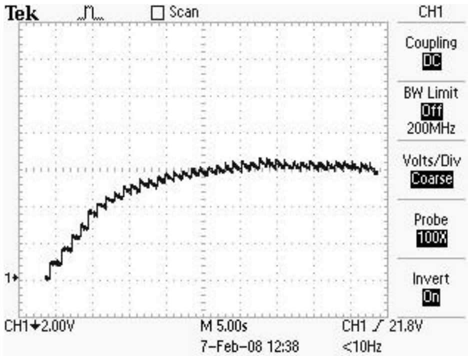


Fig. 7. The charge of buffering capacitor (10 nF) by the slowly (0.1 Hz) oscillating electrostatic energy harvester with spiral electrodes. The oscilloscope input (1 MOhm) is connected with additional load, 49 Mohm to decrease the discharge of capacitor. Therefore the maximal voltage is 3V (not 6V). The saturation of voltage occurs when the current through the 50 MOhm load, 1.2 μA, is equal to the supplied current.

The vertical scale in Fig. 7 is actually increased twofold (the available probe ratio 100× multiplier is used instead of the real 50×). Thus, a saturation voltage of ~3 V is achieved in this test. This is more than enough for charging a single-cell (1.5 V) battery. The energy saved in the capacitor, $E = V^2C/2 \approx 15$ μJ, is accumulated during 20 s; thus, the harvesting power is ~0.75 μW due to the leakage losses in rectifiers, capacitor and 0.6 μA current consumed by the oscilloscope. The pure converted power can be defined through the single discharge of a completely extended energy harvester capacitor through a 1 MOhm load that is shown in Fig. 8.

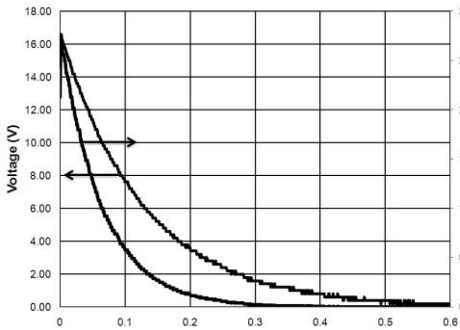


Fig. 8. Voltage and released power during the discharge of electrostatic energy harvester with spiral electrodes through a 1 MOhm load..

The integration power curve in Fig. 8 shows a released energy of ~0.326 mJ; thus, the full energy per charge-discharge cycle would be twice more, ~0.65 mJ. Therefore, the tested electrostatic energy harvester can deliver the power, $W = 0.65 \cdot f$ mW, where f is the frequency of capacitance alteration. For example, the tested prototype shown in Fig. 5(b) can oscillate with frequency ~ 10 Hz thus supplying 6.5 mW of power.

IV. Conclusion

The electrostatic swing energy harvester - oscillating, polarized charge pump - exhibits the predicted performance, and that the further optimization of materials and electronics will allow a significant increase in power output from the device. The capability to provide a DC current output with voltage >3 V was experimentally shown.

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