An Ultra High Efficiency Piezoelectric Direct Charging Radioisotope Micropower Generator

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ABSTRACT

We demonstrate a novel piezoelectric radioisotope micropower generator that has an ultra high conversion efficiency of 7.2% from collected electron energy to electrical energy. The generator employs direct charging to convert radiated β -particle kinetic energy into stored electromechanical energy, and piezoelectricity to convert the stored electromechanical energy to extractable electrical energy. The radiated β -particles are used to *direct charge* an air-gap capacitor, formed by the collector plate at the tip of a piezoelectric unimorph cantilever beam and the thin-film radioisotope source. The emitted charges induce an electrostatic force which draws the two plates closer. The collector plate eventually makes contact with the source, discharging the air-gap capacitor and releasing the cantilever. The sudden release excites the unimorph mechanical impulse response, causing the cantilever to oscillate. The stored electromechanical energy is converted into electrical energy dissipated across the load. The vibrations die out and a new reciprocation cycle begins. Using a low-activity (0.5 millicurie) radioisotope source, we demonstrate a peak output voltage of 1.5 V across a load resistance of 1 M Ω , corresponding to a peak output power of 2.25 μ W.

INTRODUCTION

A critical requirement for the success of autonomous remote systems is the realization of miniature micropower sources with long lifetimes. This demands a power source using a fuel with extremely high energy density, and a highly efficient conversion mechanism implementable at the small-scale.

Several technologies have been investigated for micropower applications. Traditional electrochemical batteries have very high conversion efficiencies (up to 50 %), but suffer from low energy densities (1-2 kJ/m³ [1]). Hydrocarbon fuels have higher energy densities (20 kJ/m³), but suffer from low conversion efficiencies at the small-scale. Demonstrated technologies for hydrocarbons conversion include micro-fuel cells [2] and micro-heat engines [3]. Micro solar cells [4] can potentially provide long lifetimes at an acceptable power density (10 mW/cm² under direct sunlight), but need light for operation.

In comparison, radioisotopes can have very high energy densities ($\sim 10^5$ kJ/m³) [5]. Additionally, since the half-life of radioisotope thin films can range from 100's of years to a few seconds, a power source with optimal lifetime can be designed with a suitable choice of radioisotope.

Early work on the conversion of radioactive energy focused on thermal heating [6], thermoelectric [7] and thermionic [8] conversion mechanisms. These mechanisms employ heat cycles and require high temperatures (300-900 K) for efficient operation. They are generally useful for the generation of power in the few watts-kilowatts range. But they do not scale down well for micropower applications. They are also feasible only at the large-scale (volume > 0.1 m³) as it is hard to achieve large thermal gradient at high temperatures in microsystems. An alternative to the

aforementioned mechanisms is direct charging of capacitors with emitted charged particles [9]. These systems can generate very high voltages (100 kV – 10 MV), but the need for power conditioning circuitry at these voltages makes this approach untenable. An approach commonly used for micro-scale micropower operation is using the betavoltaic effect (emitted charge e-h⁺ generation) [10]. Betavoltaic cells tend to be low power devices operating at low efficiencies (< 0.5 %). Moreover, they present a tradeoff between power output and lifetime as increased radiation doses can lead to limited lifetime due to impact damage.

We have previously reported a self-reciprocating direct charging cantilever beam [11] to show the feasibility of capturing the kinetic energy of emitted particles to actuate a cantilever beam, and convert the radiated kinetic energy to stored mechanical energy in the cantilever. In this paper, we report a milliscale micropower generator that utilizes the direct charging process to actuate piezoelectric unimorphs, which in turn generate electrical power. The piezoelectric unimorph supplies the load circuit with a directly usable voltage signal while shielding it from the high voltages generated due to direct charging. The generator uses a 0.5 millicurie thin-film Ni⁶³ solid source emitting low-energy β radiation (average electron energy 17 keV, half-life = 100.2 years) with very low penetration depth (14 μ m in copper). The low penetration depth of the emitted particles combined with the solid state nature of the source eliminates the need for elaborate measures for shielding, further enhancing the applicability of the microgenerator for microsystems such as remote sensor nodes.

THEORY

Figure 1 shows the schematic of the piezoelectric radioisotope micropower generator. The collector at the tip of the cantilever beam traps the charged particles emitted from the thin-film radioactive source. By charge conservation, the radioisotope film is left with equal and opposite charges. This leads to electrostatic force between the cantilever and the radioactive source, bending the cantilever and converting the radiated kinetic energy to stored mechanical energy. For suitable initial gap separations, the tip of the cantilever eventually makes contact with the radioactive thin-film and the accumulated charges get neutralized via charge transfer. As the electrostatic force is nulled, the cantilever is released. The sudden release excites oscillations, which lead to charges induced in the piezoelectric element at the base of the cantilever. With suitable termination to the electrical circuit, the cantilever system can be designed to behave as a resonant power source. A rectifier based circuit topology is commonly used to extract power [12]. The rectified output current of the micropower generator is used to charge up a storage capacitor or a rechargeable battery, which is used to power low-power circuits. In this work, a simple load resistor (Figure 2) is used to focus on the characteristics of the microgenerator.

The radiated kinetic energy E_r for one reciprocation cycle is

$$E_r = I_r E_{avg} (T_{rec} + T_{vib}) \cong I_r E_{avg} T_{rec}, \quad (1)$$

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Figure 1: Cross-section showing the geometrical parameters of the structure and a model of the air-gap capacitor. The current source is due to emitted charges, R is due to ionization current/secondary electron emission, and the source plate and the collector plate form a capacitor.

Figure 2. The circuit configuration for the characterization of the micropower generator

where I_r is the net current due to the collection of emitted charged particles, E_{avg} is the average kinetic energy of the emitted particles, T_{rec} is the reciprocation period, and T_{vib} is the duration for which the vibrations are sustained. The vibration period T_{vib} , is negligible compared to T_{rec} for the devices with high efficiency, as high charge voltages requiring long reciprocation times lead to high efficiency. The reciprocation period T_{rec} , can be calculated using

$$T_{rec} = \frac{Q_{final}}{I_r} = \frac{\sqrt{2\epsilon A k \delta_0^2}}{I_r}, \quad (2)$$

by modeling the air-gap capacitor as a current controlled electrostatic actuator. The electromechanical energy E_{em} stored in the cantilever just before discharge is

$$E_{em} = E_m + E_q = \frac{1}{2} k \delta_0^2 + \frac{Q_p^2}{2C_p} \approx \frac{1}{2} k \delta_0^2, \quad (3)$$

where E_m is the stored mechanical energy, E_q is the stored dielectric energy in the piezoelectric element, k is the stiffness of the cantilever beam, δ_0 is the initial gap height, Q_p is the charge induced in the piezoelectric just before contact due to the bending deformation and C_p is the capacitance of the piezoelectric element. For the devices discussed here, $E_m \sim 1000 E_q$. The extracted electrical energy per cycle E_{ext} , across a load resistor R_l , is given by

$$E_{ext} = \int_0^{T_{vib}} \frac{V_{out}^2(t)}{R_l} dt, \quad (4)$$

where $V_{out}(t)$ is the output voltage. The ratio of the extracted electrical energy to radiated kinetic energy η is

$$\eta = \eta_r \eta_{me} = \frac{E_{em}}{E_r} \frac{E_{ext}}{E_{em}} = \frac{E_{ext}}{E_r}, \quad (5)$$

where η_r is the ratio of the stored electromechanical energy to radiated kinetic energy and η_{me} is the ratio of the extracted electrical energy to stored electromechanical energy. The ratio η_r can be maximized by designing the peak charging voltage of the air-gap capacitor, V_{capmax} , to satisfy the following condition.

$$V_{capmax} = \sqrt{\frac{8}{27} \frac{k \delta_0^3}{\epsilon A}} = \frac{E_{avg}}{q}. \quad (6)$$

The above equation is based on the simplifying assumption that the peak charging voltage is not limited by voltage breakdown in the gap and all the emitted particles have a kinetic energy of E_{avg} . Writing δ_0 in terms of V_{capmax} and substituting the expression for T_{rec} in the expression for η_r we get

$$\eta_{rmax} = \frac{1}{2} \sqrt{\frac{27}{16}} = 0.64. \quad (7)$$

Modeling the resonant system as a single degree of freedom [13], it can be shown that η_{me} can be maximized to

$$\eta_{me} = \frac{k_{me}}{k_{me} + 2C_p c 2\pi f}, \quad (8)$$

by using an optimum value of R_l given by

$$R_{opt} = \frac{1}{C_p 2\pi f}. \quad (9)$$

Here, k_{me} is the mechanical to electrical coupling coefficient dependant on the geometry of the cantilever beam system and the characteristics of the piezoelectric element, C_p is the dielectric capacitance of the piezoelectric element, c is the mechanical damping coefficient and f is the resonance frequency of the cantilever beam system given by [14]

$$f = \frac{\lambda_i^2}{2\pi} \sqrt{\frac{k}{(0.23m + m_s)}}, \quad (10)$$

where $\lambda_i = 1.875$ for fundamental bending mode, m is the mass of the cantilever beam, m_s is the mass of the collector plate. The collector plate mass provides an additional degree of freedom in adjusting the resonant frequency without changing the stiffness of the beam (for keeping T_{rec} constant). From Equation 8, η_{me} approaches unity in the absence of mechanical damping, or,

$$\eta_{me max} = \eta_{me} |_{c \rightarrow 0} = 1.$$

Therefore, the maximum possible conversion efficiency for the device is

$$\eta_{max} \times 100 = \eta_{rmax} \eta_{me max} \times 100 = 64\%. \quad (11)$$

FABRICATION

Prototype devices are fabricated to test for the power generation characteristics and verify the conversion principle. A 100 μm thick silicon wafer is laser-cut [15] into the desired dimensions for the cantilever beam. A 125 μm thick PZT-5H (lead-zirconate-titanate oxide ceramic from Piezo Systems Inc.) plate is also laser-cut into the desired dimensions for the piezoelectric element and bonded at the base of the silicon beam. Two pieces of 125 μm thick copper sheet, cut into 1 cm $\times$ 5 mm plates, are adhesively bonded to the tip of the silicon beam to act as both a charge collector and a mass to lower the resonance frequency. A β -particle emitting ^{63}Ni radioisotope is used for all the experiments. The ^{63}Ni is electroplated as a 1 cm $\times$ 1 cm thin-film on a 1 mm thick Ni plate. A large device (5 cm $\times$ 5 mm) and a small device (15 mm $\times$ 2 mm) are fabricated and tested in a vacuum chamber (Figure 3 (a)). The smaller device is fabricated to demonstrate the feasibility of packaging the device in a ceramic DIP package (Figure 3 (b)).

TESTING AND RESULTS

Figure 3(a) shows the experimental test setup. The beam is clamped between two ceramic plates for electrical insulation. The source is clamped by two Teflon plates, which are mounted on a

Figure 3. (a) The experimental setup used for testing the prototype device. (b) A prototype generator housed in a ceramic package

linear motion stage used to control the initial distance between the source and the cantilever collector. The setup is placed inside a vacuum chamber ($p=10\text{--}20$ mTorr) sealed with a glass top. A microscope connected to a CCD camera outside the chamber is used to monitor the motion of the cantilever tip. The two leads connected to an external circuit (Figure 2) are used to monitor the output signal.

Tests for characterizing the two components of the micropower generator, the direct charging air-gap capacitor and the piezoelectric unimorph beam are carried out before the characterization of the micropower generator.

The net current due to the transport of the emitted charges I_r , is measured by positioning a collector plate ($1\text{ cm} \times 5\text{ mm}$) at a given separation from the thin-film source and measuring the short circuit (output terminals shorted) current using a semiconductor analyzer (Keithley 4200). The dependence of the charge collection on the gap separation is plotted in Figure 4. As the gap separation increases, the solid angle subtended by the collector at the source decreases, resulting in the lower number of captured particles and hence a lower current. The current is expected to be affected minimally by non-idealities in the system, such as secondary electron emission from the collector and ionization current of the residual gas molecules in the gap [12]. The measured value of the current, at a very small gap separation ($\delta_0=5\text{ }\mu\text{m}$) where the effects of the non-idealities are considered to be the least, is used in the calculation of the available energy (Equation 1) from the radioisotope source.

The stiffness of the cantilever (k) is measured by deflecting the beam tip and measuring the generated blocking force using a ChatillonTM force meter mounted on a Sutter Instruments Co. MP-285 micropositioner. The measured values of the stiffness are 2.33 N/m and 19.3 N/m for the larger and the smaller beam respectively. The measured values which agree well with the theoretical estimates of 2.67 N/m and 23.5 N/m, calculated using bending beam theory.

Tests for characterizing the micropower generator are done by first positioning the radioisotope source at an initial separation δ_0 from the collector at the tip of the cantilever, and monitoring the system through the charge-discharge/release-oscillations cycle. The reciprocation cycle is timed by visually observing for the release event. Figure 5 plots the output voltage signal from the piezoelectric element of the larger beam, with an oscillation frequency of 17.6 Hz. The procedure is carried out for different values of δ_0 and R_L . The results for the larger device are presented first.

The reciprocation period T_{rec} measured as a function of the initial gap distance δ_0 is plotted in Figure 6. The reciprocation period is expected to increase with the square root of δ_0 (Equation 2), but the measured value of T_{rec} is always higher than the expected value due to the non-idealities present in the air-gap capacitor charging system. The net radiated current I_r decreases with increasing δ_0 (Figure 4), and the leakage current due to

Figure 4. Measured net current due to the charge particles emitted from the radioisotope. Collector dimensions: $10\text{ mm} \times 5\text{ mm}$. The 2.8 pA corresponds to an effective activity of 0.5 millicurie.

Figure 5. Measured output voltage across the piezoelectric element with a 1 Mohm load.

ionization of residual gas molecules increases [12] with increasing δ_0 , resulting in higher than expected reciprocation times. Furthermore, reciprocation does not occur at all for initial gap separations of 3 mm and higher. The cantilever beam bends to about half of the gap separations, suddenly gets released and starts oscillating. This is because of the partial discharge occurring due to excessive buildup of voltage across the air-gap capacitor (estimated maximum electric field in the air gap for $\delta_0=3\text{ mm}$ is 12.75 kV/mm), illustrated by the intersection of the air-gap capacitor voltage curve with the Paschen Curve in Figure 7.

The output voltage waveform is captured, and the modal damping ratio ζ , and quality factor Q , calculated using

$$\zeta = \frac{1}{(t_2 - t_1)2\pi f} \ln \left(\frac{V_{t1}}{V_{t2}} \right) = \frac{1}{2Q} \quad (12)$$

where V_{t1} and V_{t2} are the voltage outputs at two instants t_1 and t_2 respectively, and f is the frequency of the oscillations. Figure 8 plots the Q-factor of the structure for different load resistors. As expected (Equation 8), the Q-factor peaks at a R_L of 1 M Ω .

From the output voltage waveform, the extracted electrical power E_{ext} is calculated using Equation 4. The radiated kinetic energy E_r is calculated by considering the effective number of particles captured by the collector. The effective number of particles is calculated from Equation 2. The energy conversion efficiency η , for different values δ_0 is plotted in Figure 9. The increase in η is primarily due to the increase in η_r . As δ_0 increases, the peak voltage across the air-gap capacitor V_{capmax} , increases (Equation 6). This requires the emitted particles to expend more energy to get to the cantilever collector against the higher impeding voltage, resulting in larger stored electromechanical energy. So large gap separations are desirable for higher efficiency,

but the voltage breakdown of the gas in the air-gap limits the maximum efficiency achievable.

Table 1 summarizes the results obtained from the testing of both large and small devices. The larger device gives higher efficiency at a lower voltage while the small device gives lower efficiency at a higher voltage. Generally, beams with lower stiffness placed at higher gap separations are more efficient.

	δ_0 (μm)	T_{rec} (min)	T_{vib} (s)	V_{out} (V)	E_{ext} (μJ)	E_r (μJ)	η (%)
Large	2000	73	20	1.4	6	83.33	7.2
Small	750	126	2	4.4	1.42	66.67	2.1

Table 1. Summary of the test-results on the large (5 cm $\times$ 5 mm) and small (15 mm $\times$ 2 mm) devices.

Figure 6. Measured reciprocation time vs. initial gap for a beam with a given stiffness of 2.34 N/m

Figure 7. The breakdown at gap separations larger than 2 mm is illustrated by the intersection of the calculated Paschen curve and the voltage curve.

Figure 8. Q -factor vs. R_l . The graph shows the Q -factor rising steadily till the optimum load resistance of 1 Mohm.

Figure 9. Absorbed kinetic energy to extractable electrical energy conversion efficiency vs. initial gap for beam stiffness = 2.34 N/m

CONCLUSIONS

A high efficiency piezoelectric radioisotope powered micropower generator is designed, fabricated and experimentally characterized. The ultimate limits on efficiency are identified as being the breakdown of the gas due to high voltage across the capacitor. This limit can be further explored by investigating the dominant sources of breakdown. Furthermore, by arraying many phase-locked cantilevers it might be possible to achieve high power output.

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