The Fifth International Workshop on Micro and Nanotechnology for Power Generation and Energy Conversion Applications
PowerMEMS 2005
Nov. 28-30, 2005
Takeda Hall, The University of Tokyo, Tokyo, Japan

Pathways to Near-perpetual Radioactive Micro Power Sources

Amit Lal, Hui Li, Rajesh Duggirala, Steven Tin
SonicMEMS Laboratory
School of Electrical and Computer Engineering
Ithaca, NY, USA
lal@ece.cornell.edu

Abstract

Low energy beta particle emitting radioisotopes can be relatively safe and can provide power for very long lifetime. Nickel-63 based micropower generators can theoretically last for decades to hundreds of years as the half-life of the source is 100.2 years. By using very low activity sources of 1 milli-Curie, we summarize new pathways to obtain mechanical motion, dc biases, and high efficiency nuclear to electrical power conversions. These pathways are amenable to microfabrication and integration onto integrated circuits for realizing self-powered microsystems.

Introduction

In comparison to chemical fuels, radioisotopes have very high energy densities (~10^5 kJ/m^3) [1]. Additionally, since the half-lives 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 using the kinetic energy of emitted particles [2]. The heat can then be converted into electricity using the thermoelectric [3] and thermionic [4] 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. As the size reduces, the surface to volume of the heat source increases, leading to higher percentage of heat leaked to surroundings. Although it maybe possible to reach high thermoelectric conversion at the microscale using low-thermal conductivity materials and nano-heat-transfer effects, thermal heat energy management is a tough engineering challenge at the microscale with very small thermal powers involved. An alternative to high-efficiency energy conversion is direct charging of capacitors with emitted charged particles from radioactive thin films [5]. These systems generate very high voltages (100 kV – 10 MV), which is necessary for efficient energy conversion.

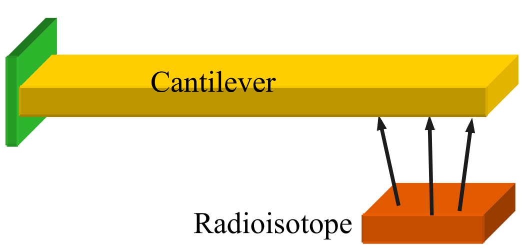

Figure 1. The radioisotope charge powered cantilever

The need for power conditioning circuitry at these voltages makes this approach untenable. Another approach commonly employed for micro-scale radioactive power sources is using the betavoltaic effect (emitted charge e-h^+ generation) [6]. Betavoltaic cells tend to be low power devices operating at low efficiencies (< 0.5 %) and have aging due to impact damage. In summary, radioisotope power generators developed before have all suffered from low energy conversion efficiencies, taking away from the high energy densities offered by radioisotope thin films.

Self-reciprocating Cantilever

The cantilever realizes a direct collected-charge-to-motion conversion. The central idea in this device is to collect the charged particles emitted from the radioisotope by a cantilever [7]. As shown in Figure 1, by charge conservation, the radioisotope thin film will have opposite charges left as it radiates electrons into the cantilever. Thus an electrostatic force is generated between the cantilever and the radioisotope thin film. The resulting force attracts the cantilever toward the source, as indicated in Figure 2. With a suitable initial distance the cantilever eventually reaches the radioisotope and the charges are neutralized via charge transfer. Although the exact mechanisms of charge transfer can be tunneling or direct contact, the time scale of the charge transfer is much shorter than the reciprocation cycle, allowing the details to be ignored for cantilever performance analysis. As the electrostatic force is decreased to zero, the spring force on the cantilever retracts it back to the original position and it begins to collect charges for the next cycle.

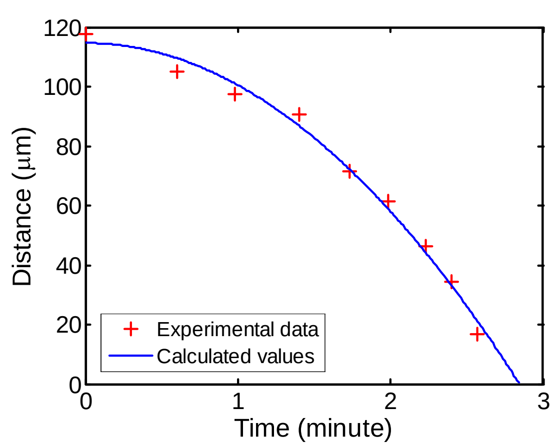

Figure 2 Distance between cantilever and radioactive source as a function of time for a cantilever with initial distance of 32 mm

Hence, the cantilever acts as a charge integrator allowing

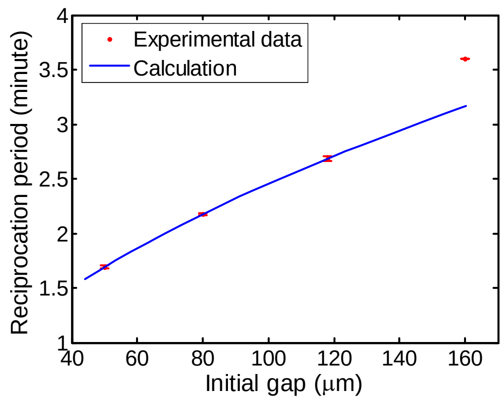

Figure 3. Reciprocation period as a function of initial gap

energy to be stored and converted into both mechanical and electrical forms.

The reciprocation period of the cantilever can be controlled by varying the gap between the emitter and collector (Figure 3). Within one reciprocation period, the energy distribution is show in Figure 4. The total energy and mechanical energy increase with time, while the electrical energy peaks and then decreases as the voltage across the capacitor decreases at smaller gaps.

The self-reciprocating cantilever converts nuclear energy to mechanical energy and can be used as a self-powered electromechanical actuator. As a mechanical actuator, the released cantilever could impact a mass for locomotion, or conversion of the mechanical energy back into electricity using the mass motion inside an electromagnet. The cantilever could also periodically deflect and modulate an incident optical, radio frequency, or ultrasonic beam, which could be useful for sensing physical or chemical variables that affect the self-reciprocation times.

Self-generated voltage bias

Micro resonators and actuators require relatively high DC bias voltages. Generating a high voltage bias from a low voltage battery requires extra circuitry and power [9]. To solve that problem, radioactive power can be used to provide a high control voltage required for tunable RF MEMS

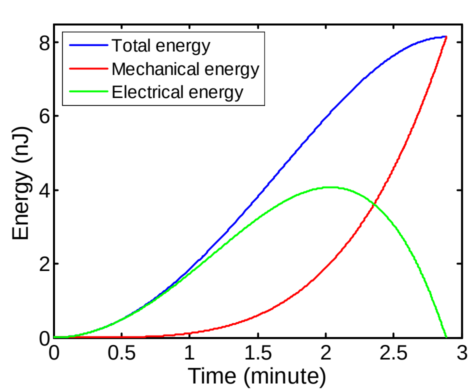

Figure 4. Energy distributions in the system at different time within one reciprocation cycle

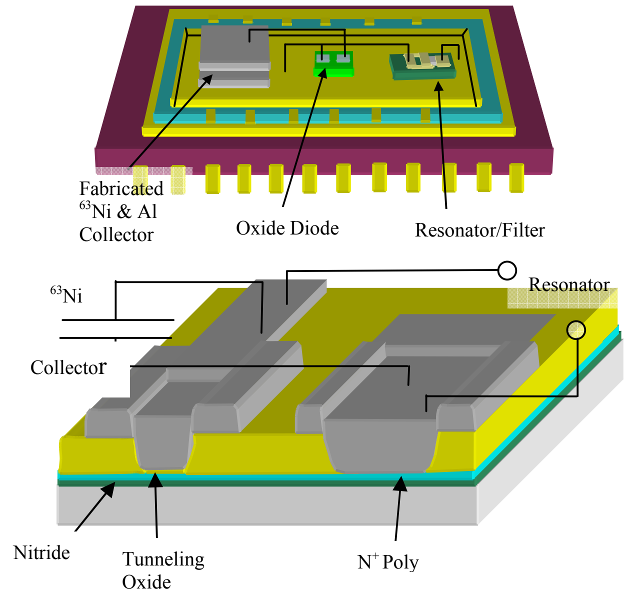

Figure 5.Top: Illustration of the assembled device with an Al plate across a Ni-63 source connected in parallel with an oxide diode and a clamped-clamped beam resonator acting as a load. Bottom: Cross-section view of oxide diode.

filter/resonators requiring zero external power. The constant voltage is generated because of the current tunneling in the oxide, which is believed to be a temperature independent process. Therefore, the bias voltage generated could also be temperature independent. Without going into the fabrication and operation details discussed in [8], Figure 5 is a schematic of the packaged device. Beta particles collected on an aluminum plate positioned 2mm above the Ni-63 electroplated, provides power for the device. High voltage bias is achieved, by charging the capacitance of the MEMS resonator, parasitic interconnects and the tunnel diode. Constant voltage is obtained when the rate of beta particle collection equals the rate of electrons leaking from the oxide diode. The constant voltage is then applied to the resonator as the DC bias voltage.

The cross section view of the oxide diode is shown in Figure 6. By varying the oxide thickness or the diode area, the

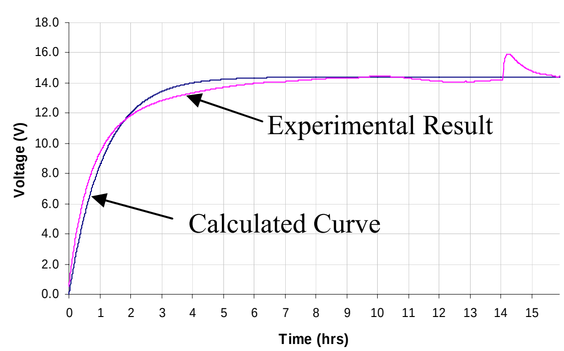

Figure 7. Oxide diode connected in parallel with 2mCi 63Ni source/collector capacitor was charged. Voltage developed across the oxide diode was sampled and plotted with time and compared with the proposed model.

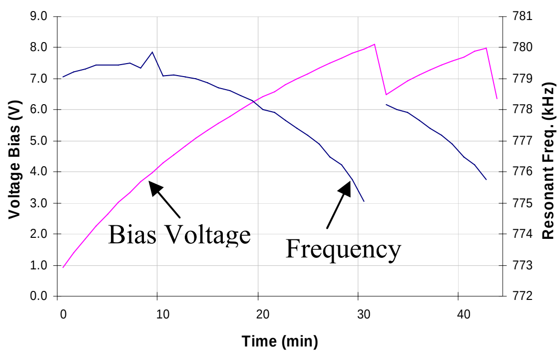

Figure 8. Plot of bias voltage and frequency as a function of time.

control voltage of the device can be set to the desired value. The voltage developed across the oxide diode when it is connected in parallel with the $^{63}Ni/Al$ parallel plate was characterized by testing the high voltage bias under a vacuum of 15mTorr. With a 2 milliCurie ^{63}Ni source, the voltage across the oxide diode reached 14 volts limited my oxide leakage currents (Figure 7).

The stabilized voltage bias was then applied to a 200x100μm clamped-clamped polysilicon beam resonator. Figure 8 shows the resonant frequency and bias voltage change as a function of time. The charge on the voltage bias was not instantly discharged, due to the time delay from the capacitor formed by a layer of native oxide on the polysilicon electrodes of the clamped-clamped beam. When the voltage drops, the electrostatic force is no longer able to overcome the mechanical force from the clamped-clamped beam, causing it to reciprocate in a shorter period. This development potentially transforms MEMS resonators into two terminal devices, as in quartz crystal, by eliminating the external bias requirements.

THE RADIOISOTOPE-POWERED PIEZOELECTRIC GENERATOR (RPG)

It is desired to efficiently convert nuclear energy into electrical energy. However, while the direct-charging parallel-plate capacitor system could be a good bias voltage source, it is very inefficient as a power supply. For self-

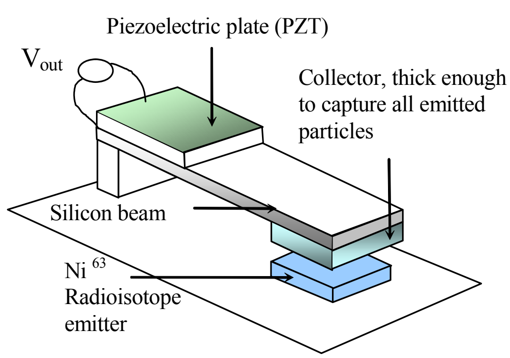

Figure 9. Schematic 3-D view of the RPG

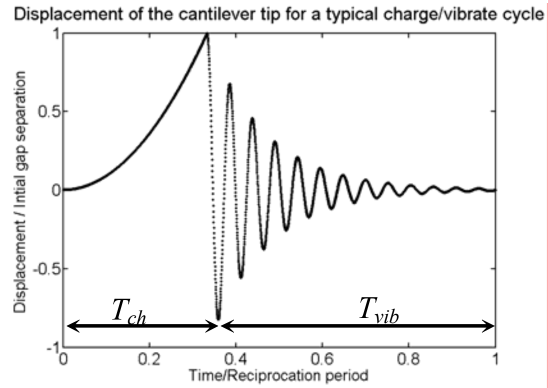

Figure 10. Plot illustrating the displacement of the tip of the cantilever in a typical reciprocation cycle

reciprocating cantilever, it can only convert nuclear energy to mechanical energy. RPG was then developed to convert radioactive energy to electrical energy with high efficiency.

As shown in Figure 9 [10], the RPG structure is the self-reciprocating cantilever with a PZT piece attached to the end the of cantilever. After the cantilever touches the radioactive source and gets discharged, the release excites the cantilever impulse response resulting in oscillations (Figure 10). The vibrations result in stressing the piezoelectric element near the anchor. The time varying stresses lead to charges induced across the piezoelectric element at the base of the cantilever (Figure 11). Thus the piezoelectric element behaves as a current source supplying any external circuit connected across its terminals with electrical power. With suitable termination to the electrical circuit, the RPG becomes a resonant power source.

The design, fabrication and power generation characteristics of the RPG are presented in detail in [11]. Here we present an elementary analysis of the device. For the purpose of analysis, a simple resistor load is assumed to focus on the characteristics of the microgenerator. The radiated kinetic energy E_r for one reciprocation cycle is

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

where N_r is the number of collected charged particles per

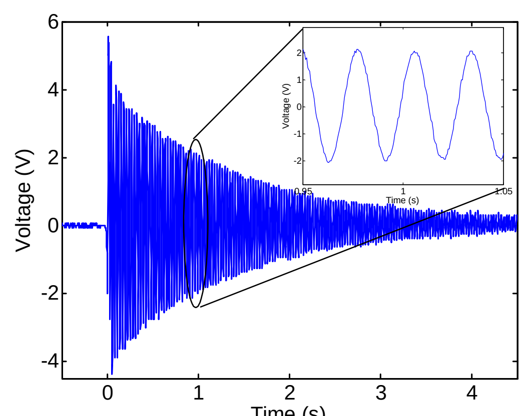

Figure 11. Measured voltage characteristics of the micro- generator after discharge, across a 1 MΩ load.

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

$$T_{ch} = \frac{Q_{final}}{I_r} = \frac{\sqrt{2\varepsilon Ak\delta_0}}{I_r}, \quad (2)$$

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

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

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, $E_m \sim 1000E_q$. 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 during the vibration period. 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 $V_{cap\max}$ to satisfy the following condition:

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

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}. However, in reality, the maximum voltage across the gap is limited by gas breakdown [16]. This in turn affects the maximum efficiencies that can be achieved.

The reciprocation period of the cantilevers can be short (100 milliseconds) or very long (1 hour), depending on the initial gap separation, for the same beam stiffness and activity of the radioisotope element. The larger the initial gap separation, the higher the final mechanical energy of the cantilever, resulting in higher available power. By careful optimization of the structure, we have demonstrated overall conversion efficiency of 7.2 %. The optimized generator goes through a charge-discharge-vibrate cycle, integrating the energy collected during the charging phase (73 min at 48 nW input energy from a weak 0.5 milliCurie source, resulting in a total energy input E_r of 83.33 μJ per cycle). This enables high power output (2.25 μW peak across a 1 MΩ load impedance, calculated from the measured voltage across a load resistance and Equation 4) for a short time during the vibration cycle, resulting in a total energy output E_{ext} of 6 μJ per cycle. The efficiency of the device can be calculated from Equation 5. Higher activity reduces the reciprocation time (Equation 2), and in some cases (activities ~ 100's of milliCurie), it may be possible to obtain continuous reciprocation, with average power output in the 10's of μW range. This may be used to power low-power electronics or trickle charge a battery. By trading off continuous power for pulsed power, high power is possible even with very low-activity radioactive sources, mitigating the safety issues with large amounts of radioactive thin film.

Summary

With high energy density, long lifetime, and probability of integration with the IC process, radioactive micro power source is a great choice for low-power on-chip IC or MEMS devices. On-chip voltage sources that can be used for biasing MEMS electrostatic actuators are demonstrated. From the self-reciprocation cantilever, which can converts radioactive energy to mechanical energy, we have developed the RPG with radioactive energy to electrical energy conversion efficiency as high as 7.2 percent, which is enough to drive low-power sensor and electronics [12]. Continued efforts at integration into CMOS will enable new functionalities even with very low amounts of radioactivity.

References

[1] Corliss W. R., Harvey D.G., *Radioisotopic Power Generation*, Prentice Hall, 1964.

[2] Stephens C. W., *Dynamic Thermal Converters, Energy Conversion Systems Reference Handbook*, Vol. III ,1960.

[3] Brauer F. B. et al., US Air Force RADC-TR-56-130, 1956.

[4] Wilson V. C., *Astronautics and Aerospace Engg.,* Vol. 1, 1963, pp. 62.

[5] Coleman J. H., *Nucleonics*, Vol.11, No.42, 1953.

[6] Guo H. et al., "Nanopower Betavoltaic Microbatteries", *Digest of Technical Papers, Transducer'03*, 2003, Vol. 1, pp. 36-39.

[7] 11. Li H. et al., "Self-reciprocating Radioisotope-powered Cantilever", *J . Appl. Phys.,* vol. 92, 2002, pp.1122-27.

[8] Kan, Shyi-Herng, Lal, A., "Self-powered IC-compatible DC-bias for Electrostatic Resonators," Proceedings of the IEEE MEMS 2004, Maastricht, Netherlands, pp. 817-820

[9] Mohan, Undeland and Robbins, " Power Electronics: Converters, Applications and design", Wiley, 1989.

[10] Lal, A., Duggirala, R., Li, H., "Pervasive Power: A Radioisotope-powered Piezoelectric Generator," IEEE Pervasive Computing Jan-Mar 2005, vol 4, no. 1, pp. 53-61

[11] Duggirala, R., Li, H., Lal, A., "An ultra-high efficiency piezoelectric direct charging radioisotope micropower generator," Technical Digest, Hilton Head '04, Hilton Head, South Carolina, USA, June, 2004.

[12] Duggirala R., Li H., Pappu A. M., Fu Z., Apsel A. and Lal A., "Radioisotope Micropower Generator for CMOS Self-powered Sensor Microsystems", to be presented in *PowerMEMS 2004*, Kyoto, Japan.