Radioisotope Batteries for MEMS

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Introduction

• Radioisotope batteries provide reliable batteries with high energy density
• They are valuable when long life is needed and recharging or refueling is difficult
• Many of the conversion technologies can function in harsh environments
• They can be very useful as onboard MEMS power sources
What is a Nuclear Battery?

• Goal: convert energy from radioactive decay to electricity
• Options:
  – Direct charge collection
  – Indirect (scintillation)
  – Betavoltaic
  – Thermoelectric
  – Thermionic
  – thermophotovoltaic
Comparison

- Consider 1 mg for power source

<table>
<thead>
<tr>
<th>Source</th>
<th>Energy Content (mW-hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chemical Battery (Li-ion)</td>
<td>0.3</td>
</tr>
<tr>
<td>Fuel Cell (methanol, 50%)</td>
<td>3</td>
</tr>
<tr>
<td>210-Po (5% - 4 years)</td>
<td>3000</td>
</tr>
<tr>
<td>3-H (5% - 4 years)</td>
<td>500</td>
</tr>
</tbody>
</table>
Isotope Selection

• Type of radiation
  – Alpha
  – Beta

• Half-Life
  – Long -> Long battery life
  – Short -> Higher power

• Avoid gammas in the decay chain

• Watch out for (alpha, n) reactions

• Watch particle range
Radioisotopes and decay

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Average energy</th>
<th>Half life</th>
<th>Specific activity</th>
<th>Specific Power</th>
<th>Power Density</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(KeV)</td>
<td>(year)</td>
<td>(Ci/g)</td>
<td>(W/g)</td>
<td>(W/cc)</td>
</tr>
<tr>
<td>63-Ni</td>
<td>17</td>
<td>100</td>
<td>57</td>
<td>0.0067</td>
<td>0.056</td>
</tr>
<tr>
<td>3-H</td>
<td>5.7</td>
<td>12</td>
<td>9700</td>
<td>0.33</td>
<td>-</td>
</tr>
<tr>
<td>90-Sr/90-Y</td>
<td>200/930</td>
<td>29/2 d</td>
<td>140</td>
<td>0.98</td>
<td>2.5</td>
</tr>
<tr>
<td>210-Po</td>
<td>5300</td>
<td>0.38</td>
<td>4500</td>
<td>140</td>
<td>1300</td>
</tr>
<tr>
<td>238-Pu</td>
<td>5500</td>
<td>88</td>
<td>17</td>
<td>0.56</td>
<td>11</td>
</tr>
<tr>
<td>244-Cm</td>
<td>5810</td>
<td>18</td>
<td>81</td>
<td>2.8</td>
<td>38</td>
</tr>
</tbody>
</table>
Specific Power Density of Leading Radioisotopes

- Po-210: 1210 Watts/cm³
- Cm-242: 882 Watts/cm³
- Cm-244: 20.4 Watts/cm³
- Co-60: 15.8 Watts/cm³
- Ru-106: 13.7 Watts/cm³
- Tm-170: 9.6 Watts/cm³
- Ce-144: 6.2 Watts/cm³
- Pu-238: 3.9 Watts/cm³
- Pm-147: 1.8 Watts/cm³
- Sr-90: 1.01 Watts/cm³
- Cs-137: 0.38 Watts/cm³
Power Density in RTG Isotopes

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Watts/gram</th>
</tr>
</thead>
<tbody>
<tr>
<td>Po-210</td>
<td>141</td>
</tr>
<tr>
<td>Cm-242</td>
<td>120</td>
</tr>
<tr>
<td>Ru-106</td>
<td>33.1</td>
</tr>
<tr>
<td>Ce-144</td>
<td>25.6</td>
</tr>
<tr>
<td>Co-60</td>
<td>17.4</td>
</tr>
<tr>
<td>Tm-170</td>
<td>13.6</td>
</tr>
<tr>
<td>Cm-244</td>
<td>2.65</td>
</tr>
<tr>
<td>Sr-90</td>
<td>0.96</td>
</tr>
<tr>
<td>Pu-238</td>
<td>0.56</td>
</tr>
<tr>
<td>Cs-137</td>
<td>0.42</td>
</tr>
<tr>
<td>Pm-147</td>
<td>0.33</td>
</tr>
</tbody>
</table>
Decay Energy of Radioisotopes

Isotope

- Cm-244
- Cm-242
- Pu-238
- Po-210
- Tm-170
- Pm-147
- Ce-144
- Cs-137
- Ru-106
- Sr90
- Co-60

Particle Energy-MeV

- Gamma Ray
- Beta
- Alpha
Direct conversion nuclear battery

- Direct conversion nuclear battery: collecting charges emitted from radioisotopes with a capacitor to achieve high voltage output
  (J. H. Coleman, 1953)

\[ V = \frac{Q}{C} \]

- 10-100 kV voltages can be created in vacuum
Static Accumulation

- Early 1950’s
- Source at K
- D is electrical insulator
- Chamber is evacuated

- 0.25 Ci Sr-90
- 365 kV
- About 1 nA
- 0.2 mW

Linder, Rappaport, Loferksi
Adding a Dielectric

- Early 1950’s
- Source at S
- D is dielectric; C is collector
- Radiation penetrates dielectric
- No need for vacuum
- High voltage
- Prevents secondary electrons from getting back to source
- 50 mCi Sr-90
- Polystyrene
- 7 kV

Keller et al
Secondary Collector

- Use beta source
- MgO used to maximize secondary’s
- Collector is graphite coated Al
- 1e-5 mm Hg vacuum
Contact Potential

- Ionize gas between two plates
- Dissimilar plates will develop potential due to differing work functions
- Low efficiency (low absorption coefficient) and high ionization energy (30 eV)
- Operates at 1-2 V

Shorr
Pacemakers

- 3 Ci Pu-238
- ~3 ounces, ~3 inches
- <mW power levels
- 100 mrem/y to patient
- Since supplanted by Li batteries (~10 yr life)
- Regulators nervous about tracking Pu

http://www.naspe.org/library/electricity_and_the_heart/
Radioisotope Thermoelectric Generators (RTGs)

- Used in many NASA missions
- Use radioisotope (usually ceramic Pu-238) to provide heat
- Electricity produced by thermoelectric
- No moving parts
- 41 have been flown by US

- Fuel: 2.7 kg. 133 kCi
- Power: 276 W
- Power (11 years): 216 W
- Total Weight: 56 kg
- Lifetime: over 20 years
- Dimensions: D=42 cm, L=114 cm
Heating Units

• NASA’s RHU
• 33 Ci
• Power is 1 W
• 1.4 oz.
• 1 cubic inch
• 2.7 g of Pu-238 (oxide form)
• Rugged, reliable

http://nuclear.gov/space/rhu-fact.html
A Compact Thermoelectric

40 mW electric power

240 cm³, 300 g total weight
Betavoltaic Microbatteries

- **First type:** planar Si $pn$-diode with electroplated $^{63}$Ni

  - Nanopower (0.04~0.24nW) obtained
  - No performance degradation after 1 year

- **Second type:** inverted pyramid array Si $pn$-diode

  - Area magnification: 1.85
  - 0.32nW (128mV/2.86nA) obtained

- **Efficiency:** 0.03~0.1% → ~10 times > micromachined RTG
Electron-Hole Pairs Generation

- Different junction depths using spin-on glass dopant diffusion
  - Boron dopant glass from Filmtronics is spinned on n-type wafer
  - Diffusion time up to 72 hours at 1050°C

- Determination if generated electron-hole pairs (EHPs)
  - 0.25 mCi is used
  - Short-circuit current is tested for each device

- Number of EHPs is obtained by dividing short-circuit current over flux of emitted electrons ($0.25 \times 10^{-3} \times 3.7 \times 10^{10} \times 1.6 \times 10^{-19}$)

- Ability of $^{63}$Ni current multiplication:
  1 electron/betas can generate ~920 EHPs in average.

- The electron emitted from Ni$^{63}$ could travel in silicon up to ~40 µm. Thus, minority carrier diffusion length $L_N > 40$ µm
MicroPower Prediction Using Higher Radioactivity

- **Currently 1mCi of $^{63}$Ni is used**
  - Source density of ~0.0625mCi/mm² → 2 ~8nW/cm²

- **10mCi~100mCi of $^{63}$Ni is expected to be used**
  - Source density is ~1~2mCi/mm²
  - 100nW ~200nW can be obtained → 100~200nW/cm²

- **Energy conversion efficiency of 0.5~1% is expected to be achieved**
  - Theoretical conversion efficiency: 3~5%
    - (920EHPs vs. 5200 (=17.3Kev/3.5eV) EHPs)
  - Leakage current density (1.5pA/mm² vs. 0.3pA/mm²) still can be reduced.
Latest Development : Using Radioisotope $^{147}$Pm

• Another way to raise power output: using high energy power source
  - $^{147}$Pm, with $E_{\text{avg}} = 62$ keV and $E_{\text{max}} = 220$ keV and half-life of 2.6 year is also a promising pure beta source for microbattery.

• Preliminary Results
  - $1 \mu$m of SiO$_2$ is used as protection layer
  - Device area: 2mm $\times$ 3mm
  - 5mCi of $^{147}$Pm is used
  - Test result: $I_s = 140nA$, $V_{oc} = 183mV$, $P_{max} = 16.8nW$
  - Conversion efficiency: 0.62%
  - Long-term stability is under test

![Graph showing current versus voltage](image)
Direct conversion of emitted charges to mechanical motion

- Low energy from source is integrated over time to achieve high instantaneous power.
- Continuous reciprocation for 4 weeks has been achieved.
Electromechanical model

Charge conservation:

\[
\frac{\alpha I}{A} - \frac{V}{RA} - \varepsilon_0 \frac{\partial}{\partial t} \left( \frac{V}{d} \right) = 0
\]

Force balance:

\[
k(d_0 - d) - \varepsilon_0 A \frac{V^2}{d^2} = 0
\]

\[
\frac{\partial d}{\partial t} = \frac{2}{\varepsilon_0 RA} (d_0 - d) d - \frac{2\alpha I}{\sqrt{\varepsilon_0 kA}} \sqrt{d_0 - d}
\]
Previous work: self reciprocating cantilever: SIZE

- Initial gap ($d_0$): 33 μm
- Period: 6 min. 8 sec.
- Residual charges: $2.3 \times 10^{-11}$ C
- Peak force ($k d_0$): 10.1 μN
- Assumed Collection efficiency ($\alpha$): 10%
Self-reciprocating SiN cantilever

- The cantilever is made of low stress SiN thin film with dimensions $500 \ \mu m \times 300 \ \mu m \times 1.7 \ \mu m$.
- The cantilever is mounted on a DIP package for wire bonding.
- Four poly resistors form a Wheatstone bridge to measure the deflection of the cantilever.
- The signal from the Wheatstone bridge is sent to an instrumentation amplifier and then output from the amplifier is measured.
Self-powered: Sensor/Actuator/Transmitter: Reciprocation of a PZT beam results in RF output

- Sudden current release results in excitation of electrical and mechanical modes of the system
- RF frequency of 60-260 MHz due to distributed waveguide
- Thickness mode of PZT at 21 MHz results in modulation of RF => mechanically sensed signal can be transmitted as RF in a highly compact manner
Self-powered RF Pressure Sensor

Figure 8. A PZT cantilever is mounted inside a chip carrier. A self made coil is soldered to it. The glass cover is glued to the package with a high molecular weight vacuum wax that can provide good sealing for the vacuum needed. An inlet on the backside provides connection to a vacuum system.

Figure 2. The current provided by the $^{63}$Ni source varies with the pressure.

Figure 5. (a) The capacitance of the piezoelectric cantilever builds up an electric field as the charges are built on the two electrodes. (b) The sudden shorting of the charge on one side results in a sudden release of the electric field and hence the voltage across the cantilever. This results in a current $I = C_1 \frac{dV}{dt}$ that excites the dielectric RF mode of the PZT.

Figure 9. A typical pulse detected by the coil placed 0.1 m away from the DIP package. The frequency is 100 MHz. The peak-to-peak voltage is 138 mV.
Summary

- Radioisotopes provide a high energy density power source suitable for many applications
- They are outstanding for small scale power