Nanotechnology and Energy Harvesting from Radioisotopes

Larry L. Gadeken, BetaBatt

MEPTEC 9th Annual MEMS Symposium
19 May 2011
Outline

What is …

➤ Energy Harvesting
➤ Basic Nuclear Concepts
➤ Current Micro-/Nano-Technology Developments
➤ Potential Nanotechnology Solutions
➤ Future Outlook
Power versus Energy Comparison

Ragonè Plot for Batteries and Betavoltaics

Specific Energy (W-hr/kg)

Specific Power (W/kg)

24% 35Ni (T1/2 = 100 yr)
3D SiC
3D Si
11.4 yr
1.14 yr
5.95 wk
4.17 dy
10 hr
1 hr
6 min
36 sec
3.6 sec

Battery & Capacitor Data from http://berc.lbl.gov/venkat/Ragone-construction.pps
Radioisotope Types

- **Alpha emitters** –
  - release energetic He nuclei – (4-6 MeV/particle)

- **Beta emitters** –
  - emit electrons or positrons (and neutrinos) –
  - (10s–100s keV with characteristic energy spectra)

- **Gamma emitters** –
  - Nucleus emits very energetic photons
    (electromagnetic ‘rays’ – highly penetrating)

Note: X-rays are photons emitted by very excited atoms.
What is a Nuclear Battery?

- Convert energy of radioactive decay into electricity
- Options:
  - Direct charge collection
  - Indirect (convert to light for photovoltaic)
  - **Betavoltaic**
  - Thermoelectric
  - Thermionic
  - Thermophotovoltaic
Isotope Selection

- **Type of radiation**
  - Alpha (α)
  - Beta (β)

- **Half-Life**
  - Long - Long battery life (238-Pu: 0.6 W/g, $T_{1/2}=86$ yr)
  - Short - Higher power density (210-Po: 137 W/g, $T_{1/2}=4$ mos)

- **Cost**
  - Design for particle range, displacement damage
  - Avoid gamma rays. Reduce Brehmstrahlung (safety)
  - Watch out for (α, n) reactions
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 mos) →α</td>
<td>3000</td>
</tr>
<tr>
<td>3-H (5% - 4 years) →β</td>
<td>500</td>
</tr>
</tbody>
</table>
Radioisotope Thermoelectric Generator

- Used in many NASA missions
- Use ceramic loaded with Pu-238 for heating
- Thermoelectric power generation

- 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
Pacemakers (circa 1970)

- 3 Ci Pu-238
- ~3 ounces, ~3 inches
- <mW power levels
- 100 mrem/y to patient
- Since supplanted by Li batteries (~7 year life)
- Regulators nervous about tracking Pu
- Thermoelectric (some betacell concepts)

http://www.naspe.org/library/electricity_and_the_heart/
Self reciprocating cantilever

- Initial gap ($d_0$): 33 µm
- Period: 6 min. 8 sec.
- Residual charges: $2.3 \times 10^{-11}$ C
- Peak force ($kd_0$): 10.1 µN
- Assumed Collection efficiency ($\alpha$): 10%
Continuous Charger Technology

The BetaBattery™ – A Long-Life, Self-Recharging Battery

- STORAGE — Thin-film rechargeable Lithium battery
- CHARGER — Tritiated 3D Silicon Diodes
- CASE — Safely encapsulate active components
Self-Recharging BetaBattery™

- Ultra long-life battery pack with built-in charger
  - Low power applications (<10V, <100μA, <1000 μW)
  - Flexible duty cycle (e.g., 4 mA for 1 sec. every 3 min.)

- Enabling platform technology
  - Perform extremely high value tasks
  - Importance great compared to power cost

- Proven and proprietary IP
  - Own basic patents
  - Developed through SBIR grants from NSF
  - Sponsored university research licensed
Prototype BetaBattery Fabrication

BetaBattery Fabrication Steps
Assembly Procedure
Maximizing Efficiency

- **Cost**
  - Radioisotopes are very expensive
  - Want to maximize energy conversion

- **Geometry**
  - Locate decaying nuclei adjacent to converter
  - 3D configuration
  - Minimize volume of inactive materials
  - Converter dimensions commensurate with range

- **Flexible source manipulation capability**
Thin, Flexible Semiconductors

- For low energy beta emitters, source layers must be thin (sub-micron)
- Range of particles in semiconductor is also a few microns at most
- Hence, thin semiconductors are an advantage
- Multi-layer devices can offer good power density with good efficiency
Tritiated Butyl Rubber Molecule

- Synthesis procedure can be ‘tuned’
  - Polymer can be solid or liquid
  - Liquid can be solidified by ‘cross-linking’
- Enables flexible device geometry
  - Maximize delivery of energy to converter
  - ‘Harvest’ most tritium decay energy
- U.S. Patent 7,622,532
Nanotechnology Potential

- Converter
  - Nano particle diodes, carbon nanotube diodes
  - Nano printing techniques for device fabrication
  - Self assembly using micro- or nano-fluidics

- Graphene
  - Usage as electrode

- Energy Source
  - Continuous production in film format

- Substrate Development
  - Film transfer and release
Device Fabrication

- Manufacturing Issues
  - Macro scale devices from nano scale components
  - Cost-effective means of energy source preparation
  - Efficient methods of integrating energy source and converter device and film assembly procedures

- Radioactive Materials Handling
  - Minimize waste generated
  - Minimize manipulation of radioactive materials
  - Maximize safety for personnel, users and public
## Potential Markets

<table>
<thead>
<tr>
<th>Category</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Government &amp; Military</td>
<td>Anti-Tamper and Security, Sensors and Detectors, Health Monitoring of “Smart” Electronics, Covert Operations and Intelligence</td>
</tr>
<tr>
<td>Human Health</td>
<td>Cardiac Rhythm Management (Pacemakers) Micro stimulators and Drug delivery, etc.</td>
</tr>
<tr>
<td>Subsea</td>
<td>Valves and Actuators Sensors and Controls Telemetry</td>
</tr>
<tr>
<td>Subsurface</td>
<td>Real-Time Measurements 4D Seismic</td>
</tr>
<tr>
<td>Outer Space</td>
<td>Space Vehicles, Satellites</td>
</tr>
<tr>
<td>Micro-Electronics</td>
<td>Microelectronic Mechanical Systems (MEMS) <strong>Self-Powered Electronic Circuitry</strong></td>
</tr>
<tr>
<td>Communications/Sensors</td>
<td>RFID Tags Implanted Microcircuits</td>
</tr>
</tbody>
</table>
Market Applications
  - Justify cost and risk of using radioisotope fuels
  - Advantage is very long life

Power Delivery
  - Prototypes now: 10s – 100s nanoWatts/device
  - Production soon: 200 – 2000 microWatts/cm³

Nanotechnology will play a role

Success
  - Requires significant research and engineering development supported by adequate funding
A Wake-Up Call

Fukushima Daiichi

Close the Nuclear Fuel Cycle

Support Japan’s Recovery
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>0.0000083</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>

Key Take Away: Average range for $\alpha$ and $\beta$ particles is 1-10 $\mu$m.
First type: planar Si $p/n$-diode with electroplated $^{63}$Ni

- DIP package
- Leads
- Glass
- Electroplated $^{63}$Ni thin film

Second type: inverted pyramid array Si $p/n$-diode

- Area magnification: $1.85 / 0.32$ nW ($128$ mV/$2.86$ nA)
- Efficiency: $0.03$~$0.1\%$
- $\sim 10$ times $>$ micromachined RTG

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

$^{63}$NiCl/HCl solution ($8\mu$Ci/µl)
Wide Bandgap Semiconductors

- Silicon carbide, etc.
  - Wider bandgap will produce greater conversion efficiencies
  - Simulations indicate as much as 25% possible