Chapter 2
Radioisotope Thin Films
for Microsystems

2.1 Introduction

Radioisotopes can be employed in microsystems in a variety of ways to exploit the many unique properties of radioactivity:

1. The kinetic energy of the emitted radiation can be converted into electrical energy for micropower generation
2. The energetic charged particles emitted can be directly collected and charge-separation based electrostatic actuation of cantilevers can be enabled for autonomous sensors
3. The near constant probability of decay of nuclei could be utilized for realizing frequency standards.

This chapter serves as an introduction to the aforementioned applications of radioisotopes in microsystems, and the subsequent chapters provide the details.

2.2 Radioisotope Micropower Generation

Autonomous microsystems deployed in remote locations need to have long lifetimes to avoid prohibitively expensive periodic replacement. Additionally, some autonomous microsystems need to be very compact (< 1 cc), so they can be deployed in small spaces. Applications requiring such compact long-lifetime autonomous microsystems include the low power wireless sensors that promise to revolutionize applications ranging from environmental monitoring [13, 14] to civil infrastructure health monitoring [15], and implantable medical devices such as pacemakers [11] and intracranial implants [16].
Compact microsystems with long-lifetimes can be realized by employing low power sensor and wireless communication subcomponents [17] powered by compact high energy capacity microbatteries. Low power sensors can be realized by taking advantage of the recent advances in microelectromechanical systems (MEMS) based transducer and packaging technology, and low power wireless signal generators can be realized using advanced CMOS integrated circuits. Compact high energy capacity microbatteries can be realized either by using high energy density fuels.

In particular, high energy density ($\approx 1–100 \text{ MJ/cc}$) radioisotope fuels with long half-lifetimes (1–100 years) are employed in this book to realize high energy capacity microbatteries. In comparison, conventional electrochemical and hydrocarbon fuels offer energy densities of 1–5 kJ/cc [18] and 10–20 kJ/cc [19] respectively. Radioisotope fuels are also reliable under severe ambient conditions, as they emit radiation from spontaneously decaying at a rate that is almost invariant with ambient conditions.

### 2.2.1 Radioisotope Thin Film Fuels

In this book, the radiation kinetic energy emitted from thin films of radioisotopes is harvested to generate electrical energy. The radiation energy emitted from radioisotopes can be in the form of: doubly charged helium ions emitted with average energy $E_{\text{rad,avg}} > 5 \text{ MeV}$, called $\alpha$ radiation; electrons ($\beta^-$) and positrons ($\beta^+$) emitted with $E_{\text{rad,avg}}$ ranging from 5.3 keV to 2 MeV, called $\beta$ radiation; and highly energetic electromagnetic radiation or photons emitted with $E_{\text{rad,avg}}$ in the range of MeV’s, called $\gamma$ radiation. The selection of radioisotope fuel for any application is determined by the microbattery requirements of output power density, energy density, cost, and lifetime, and safety limitations (Table 2.1).

### 2.2.2 Power Density, Energy Density, and Lifetime of Radioisotope Fuels

The radiation power density $P_{g,\text{dens}}$ generated within a radioisotope fuel can be written as

$$P_{g,\text{dens}} = 3.7 \times 10^{10} \times SA_r \times \rho_r \times E_{\text{rad,avg}}, \quad (2.1)$$
Table 2.1: Comparison of radiation properties of $^3$H, $^{63}$Ni, and $^{147}$Pm thin films

<table>
<thead>
<tr>
<th>Parameters</th>
<th>$^3$H</th>
<th>$^{63}$Ni</th>
<th>$^{147}$Pm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Half-life (years)</td>
<td>12.4</td>
<td>100.3</td>
<td>2.64</td>
</tr>
<tr>
<td>Radiation type</td>
<td>$\beta^-$</td>
<td>$\beta^-$</td>
<td>$\beta^-$, weak $\gamma$</td>
</tr>
<tr>
<td>$E_{rad,avg}$ (keV)</td>
<td>5.7</td>
<td>17.3</td>
<td>63.5</td>
</tr>
<tr>
<td>$E_{rad,max}$ (keV)</td>
<td>18.6</td>
<td>63</td>
<td>220</td>
</tr>
<tr>
<td>Highest available specific activity</td>
<td>500</td>
<td>133</td>
<td>4300</td>
</tr>
<tr>
<td>(curie/cc)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Optimal layer thickness for $\eta_r &gt;75%$ (μm)</td>
<td>0.1</td>
<td>0.8</td>
<td>6</td>
</tr>
<tr>
<td>Power density ($\mu\text{W/cm}^2$)</td>
<td>0.7</td>
<td>0.45</td>
<td>827</td>
</tr>
</tbody>
</table>

where $SA_r$ and $\rho_r$ are the specific activity (curies/g) and density (g/cc) of the radioisotope source respectively, and $E_{rad,avg}$ is the average energy of the particles or radiation emitted. For maximizing $P_{g,dens}$ in any material, it is desirable to maximize $SA_r$ by enriching the radioisotope fuel. Furthermore, since $P_{g,dens}$ decreases exponentially with time following the decrease in $SA_r$ as

$$SA_r(t) = SA_r(0)e^{0.3t/\tau_{1/2}},$$

it is desirable to select radioisotopes with long half lifetimes $\tau_{1/2}$ for high energy capacity.

A portion of $P_{g,dens}$ is self-absorbed by the radioisotope fuel [3], and the rest is emitted to produce radioisotope fuel output energy density $P_{r,out}$ given by

$$P_{r,dens} = P_{g,dens} \times \eta_r.$$  

Here, $\eta_r$ is the energy emission efficiency of the radioisotope fuel, and depends on the geometric form factor.
2.2.3 Review of Radioisotope Micropower Generation

Radioisotope energy can be converted to electrical energy at the micro-scale in any of the previously developed energy converters (Fig. 2.1): (1) thermoelectric engines; (2) direct charge nuclear batteries; (3) direct conversion batteries; or (4) indirect conversion batteries.

Thermoelectric engines first convert the kinetic energy of the particles into heat via collisions against target particles, and then transform the heat into electricity either by dynamic heat engines or by direct conversion devices such as thermoelectrics [1, 2] (Fig. 2.2). Thermoelectric conversion schemes tend to be inefficient at the micro-scale because it is difficult to realize high temperatures or large heat gradients at the micro-scale. The surface to volume ratios tend to be high at the micro-scale, and heat losses

Figure 2.1: Schematic illustrating the various radioisotope energy conversions, including the newly developed radioisotope electro mechanical power generation presented in this book
can be significant. Additionally, realization of high temperatures can require large activities of the radioisotope, and that limits their utility in microsystems use where radiation safety is important. Therefore, nuclear batteries, radioisotope energy converters that do not use heat cycles, are more applicable at the micro-scale. Nuclear batteries here refer to the radioisotopic power generators that do not use heat engines in the energy conversion process.

**Direct Charge Nuclear Battery**

A direct charge nuclear battery generates electricity by collecting the charged particles emitted by radioisotopes across an air-gap or dielectric capacitor, and supplying any electrical load with that charge at a voltage that builds up across the capacitor because of the charge separation (Fig. 2.3). Generally, a direct charging nuclear battery is made up of two electrically isolated concentric spheres or coaxial tubes or parallel plates acting as two electrodes, and the space in between filled with vacuum or a dielectric material that does not absorb the radiation. One electrode is coated with the radioisotope thin-film, and the other electrode acts as the charge collector. Electrical loads are connected across the two electrodes. This type of battery was first demonstrated by Moseley in 1913 [20].
Figure 2.3: Schematic illustrating a radioisotope direct charging generator

Direct charged nuclear batteries typically supply low current (≈nAs) at very high voltages (up to hundreds of kVs). The current is determined by the activity of the radioisotope. For example, the current outputs of 1 millicurie $\alpha$ and $\beta$ radioisotopes is just $5.9 \ pA$ and $11.8 \ pA$ respectively. The operating voltage of the battery depends on the maximum energy of the emitted charged particles, charge leakages in the air gap, and the electrical load. The efficiency of energy conversion depends on the ratio of the battery voltage to the average kinetic energy of emitted particles, as that is the energy each emitted charge particles transfers to the electrostatic system while overcoming the built up voltage. Therefore, high energy conversion efficiency requires voltages to be built up across the capacitor, which greatly limits the application of this battery.

**Direct Conversion Nuclear Battery**

Direct conversion nuclear batteries operate by utilizing the radiation output of a radioisotope to ionize atoms in a medium between two electrodes, and use a voltage gradient set-up between the two electrodes to separate and collect the ionized charges and supply to any electrical load connected across the two electrodes. Each ionizing particle or quanta in the radiation can ionize many atoms, depending on the ratio of the average kinetic energy of the ionizing particle and the average ionization energy for the atoms. Since the
average ionization energy for most atoms tends to be in the range of 1–100 eV, and most radioisotopes emit radiation with average kinetic energy ranging from keV to MeV, a much larger current can be realized using direct conversion nuclear batteries compared to direct charged nuclear batteries. The voltage gradient can be realized using one of two ways. The two electrodes in the battery can be constructed from two different metals, and the contact potential difference between the two can be used for producing the voltage gradient. Such batteries are called contact potential difference (CPD) battery (Fig. 2.4). Alternatively, the two electrodes could be across p-n junctions, and the electric fields set-up across the depletion region could be used to separate the charged particles (Fig. 2.5).

In a CPD battery, the open circuit voltage, defined as the voltage that builds up across the battery when there is no load connected across its terminals, equals the contact potential difference between the two metals, which is generally equal to or

![Figure 2.4: Schematic illustrating a radioisotope powered contact potential difference generator](image)

![Figure 2.5: Schematic illustrating a radioisotope powered electronvoltaic generator](image)
less than one volt [21]. While a CPD battery can be constructed by depositing the radioisotope on one of the electrodes and filling up the gap between the electrodes with a gas, an alternative is to fill the gap between the two electrodes using a gaseous mixture containing a gaseous radioisotope source. In such a battery, a large part of the beta particle energy can be transformed into useful current, as there are no losses of kinetic energy due to self-absorption inherent in solid sources. An example of a gaseous radioisotope is $^{3}$H, which can be mixed uniformly with some other gas. The CPD battery using tritium gives about 100 times the current from the beta source itself [22]. However, even though the current is higher for a CPD nuclear battery compared to a direct conversion type nuclear battery, it is still small in absolute value. And for the ionization of the working gas to be efficient, the size of the CPD nuclear battery has to be large. Furthermore, the battery itself has a very high electrical impedance since the two electrodes form a capacitor. This limits the utility of CPD nuclear batteries in microsystems.

In an electronvoltaic battery, the open circuit voltage depends on the energy band-gap of the semiconductors used in the junction. For silicon electronvoltaics, it can be up to a few 100 mV. Larger voltages can be realized by connecting several cells in series. Since each electron-hole pair generation requires $\approx 3$ eV, large current multiplication factors can be realized. For example, one $\beta$-particle from strontium-90 produces about 200,000 electron–hole pairs. However, one important drawback of junction-type nuclear batteries is that the lattice structure in the p–n junctions is susceptible to radiation damage, and subsequently, degradation in performance. This typically starts becoming important when the energy of charged particles exceeds a certain threshold, about 200 keV for Si [22]. Since for most radioisotopes the average energy of the emitted charged particles tends to be larger than 200 keV, electronvoltaic based nuclear batteries tend to have short lifetimes. Since $\alpha$-particles are much bigger and their kinetic energies are generally greater than 1 MeV, silicon alpha voltaic batteries have very limited lifetimes. In contrast, low power $\beta$-particle powered silicon electronvoltaic based nuclear batteries can have long lifetimes [11].
Indirect Conversion Nuclear Battery

Indirect conversion nuclear batteries operate by first converting the kinetic energy of charged particles into light by irradiating radioluminescent materials, and then converting the generated light into electrical energy using photovoltaics [1] (Fig. 2.6). By introducing the intermediate energy conversion step, the radiation sensitive photovoltaic elements are partially shielded from radiation damage. However, since it takes two processes to generate electricity, the efficiency of each process has to be relatively high for a good overall energy conversion efficiency. The efficiency of the first step can be improved by realizing high absorption of emitted particles in the phosphor, improving the conversion from nuclear energy to light, and by minimizing the light absorption in the phosphor. The efficiency of the second step depends on the fraction of the light that can be absorbed in the depletion region of the solar light, and on the energy band gap of the semiconductor used in the solar cell. While reasonable energy conversion efficiencies can be realized, the partial exposure of the solar cell may still result in damage and cause performance degradation.

2.2.4 $^{63}$Ni Micropower Generation

Thin film $^{63}$Ni is well suited for long lifetime safe microsystems because of its 100 year half-lifetime and its relatively low radiation and chemical risk. Thin films of $^{63}$Ni can be handled with minimal shielding requirements, because the $E_{^{63}Ni, avg} = 17.3$ keV
\(\beta\)-electrons cannot penetrate the dead layer of human skin [3], and the resulting Bremsstrahlung is insignificant. Additionally, \(^{63}\text{Ni}\) is not known to effuse out of thin films at temperatures as high as 400°C. Consequently, it is employed in a variety of industrial applications including electron capture devices [9]. However, \(^{63}\text{Ni}\) thin films suffer from very low power densities (0.1–1 \(\mu\)W/cm\(^2\)), and lead to microbatteries with low power densities (< 50 nW/cm\(^3\)) [23]. Therefore, \(^{63}\text{Ni}\) microbatteries have found limited use in microsystems, which typically require 0.1–100 mW/cc.

In this book, the low power output limitation of \(^{63}\text{Ni}\) thin films is overcome by employing them to fuel pulsed power microbatteries (Chaps. 3 and 4), so their 0.1–1 \(\mu\)W/cm\(^2\) power output can be integrated to produce 0.1–1% duty cycle 0.01–1 mW/cc electrical power pulses (Fig. 2.7) useful for periodically sampling wireless sensor microsystems (Fig. 2.8) [17].

Furthermore, pulsed electrical power can be generated from \(^{63}\text{Ni}\) thin films by employing any of the above energy converters to convert the low <1 \(\mu\)W/cm\(^2\) radioisotope power to electrical power, integrating the electrical power using energy storage elements such as capacitors, and using low-duty cycle switching for pulsed discharge of the stored electrical energy across loads (Fig. 2.9). However, practical switches for isolating the storage capacitors from loads during the integration phase typically have leakages that result in inefficient integration of < 1 \(\mu\)W electrical power for pulsed electrical power generation. This problem is overcome using a novel electromechanical energy converter that efficiently integrates the low 0.1–1 \(\mu\)W/cm\(^2\) \(^{63}\text{Ni}\) power output to generate: (a) continuous power output of 10–100 nW/cc; (b) 0.1–1% duty cycle 0.01–1 mW/cc power pulse; and (c) 0.1–1% duty cycle discharge generated wireless RF pulses detectable up to 3.6 m, with an overall energy conversion efficiency of 4.13%.

The electro-mechanical converter consists of a radioisotope actuated reciprocating piezoelectric unimorph cantilever with integrated betavoltaics [24], and is an extension of the radioisotope-powered self-reciprocating cantilever demonstrated previously [25, 26]. Figure 2.10 illustrates the operating principle of the self-reciprocating cantilever, where a radioisotope thin film emitting
Figure 2.7: Schematic illustrating the performance space of the radioisotope powered microbatteries and zero-power sensors developed in this book. The $^{147}\text{Pm} - \text{Si}$ betavoltaic microbattery performance is estimated based on the design and performance of realized 3D silicon betavoltaics.

energetic charged particles is used to electrostatically actuate a cantilever. The actuation charges increase with time, resulting in the cantilever deformation increasing with time. Thus, the cantilever acts a mechanical energy integrator. 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 and set into vibrations. Thus, the integrated stored mechanical energy is released as a pulsed mechanical energy output. This pulsed mechanical energy can be converted into a pulsed electrical energy output by attaching a piezoelectric element to the cantilever. The piezoelectric element
Figure 2.8: Schematic illustrating the power requirements of typical periodically sampling low power wireless sensor microsystems. The axes are not to scale.

Figure 2.9: Schematic of a pulsed electrical power generator that integrates the continuous power output of a radioisotope power generator across a storage capacitor, and uses low duty cycle switching for pulsed discharge of the stored electrical energy across the load.
Figure 2.10: Schematic illustrating the radioisotope actuation of self-reciprocating cantilevers, and the generation of electrical energy when the cantilever is a piezoelectric unimorph produces electrical charges in response to the mechanical deformations during cantilever vibrations, and converts the stored mechanical energy into electrical energy (Fig. 2.1). The piezoelectric unimorph also acts as a transformer, generating a directly usable voltage signal (≈1 V) from the high air-gap voltages (few kVs) generated due to direct charging from the radioisotope film. Hand assembled macro power generators were tested with four 3 millicurie $^{63}$Ni sources to yield a maximum power output of 750 $\mu$W and a maximum energy conversion efficiency of 3.94% efficiency (Appendix B).

**MEMS Reciprocating Electro-Mechanical Power Generators**

Previously demonstrated hand-assembled radioisotope powered electro-mechanical power generators (REMPG’s) [24] comprised of piezoelectric unimorph cantilevers fabricated by adhesively bonding bulk piezoelectric (lead zirconate titanate, PZT) plates (125 $\mu$m thick) to copper sheets (125 $\mu$m). The resulting beams were > 4 cm long, because the unimorph cantilever stiffness had
to be low enough (1–10 N/m) for radioisotope actuation to result in pull-in and discharge. This limited the radioisotope fuel fill factor \((FFF)\), or the ratio of the volume of the fuel to the total volume of the generator, which in turn limited the REMPG energy and power output density \(P_{out,rempg,dens}\), because

\[
P_{out,rempg,dens} = P_{r,dens} \times FFF \times \eta_{rempg},
\]

where \(\eta_{rempg}\) is the REMPG energy conversion efficiency. Additionally, the lossy adhesive and bulk materials limited the REMPG energy conversion efficiency of stored electromechanical energy to electrical energy to < 60%.

To overcome these limitations, microfabricated radioisotope-actuated reciprocating electro-mechanical generators that achieve higher fuel fill factors at milli-scale have been developed. The unimorph cantilevers are fabricated by deep reactive ion etching (DRIE) silicon cantilevers coated with either sol-gel deposited PZT thin films or RF sputtered aluminum nitride (AlN) thin films. The resulting high quality interfaces and low loss silicon cantilevers also lead to higher stored electromechanical energy to electrical energy conversion efficiency. Furthermore, the microfabricated REMPGs can be readily integrated with on-chip microsystems.

Multiple Power-Output Integrated Radioisotope Electro-Mechanical Power Generators (IREMPG)

The energy conversion efficiency of the REMPG is proportional to the gap voltage \(V_{gap}\) built up across the direct charging electrostatic gap, because the radioisotope energy to electromechanical energy conversion occurs when the \(\beta\)-electrons spend energy \(qV_{gap}\) in overcoming the impeding electric field to cross the gap. The gap voltage should ideally be 17.3 kV, so the \(E_{63^{\text{Ni}},avg}=17.3\) keV electrons can transfer all of their kinetic energy in overcoming the impeding electric field across the gap. However, charge leakages through the vacuum in the gap limit the maximum realizable \(V_{gap}\) to <5–10 kV. Furthermore, the \(V_{gap}\) versus time profile resulting from the gradual charging up of the air-gap results in even lower \(V_{gap,avg}\). Therefore, only a fraction of the 17.3 keV is
Figure 2.11: Schematic illustrating IREMPG construction, and snapshot of operation during the charging phase. The $^{63}$Ni thin film is charged to voltage $V_{\text{gap}}$, and the $\beta$-electrons expend energy $qV_{\text{gap}}$ in overcoming the impeding electric field before reaching the collector on the piezoelectric unimorph transferred to the electromechanical system, and the rest is dissipated as heat in the collector. A portion of the remaining kinetic energy can be used to generate electron-hole-pairs (EHPs) in a betavoltaic integrated at the collector (Fig. 2.11), and the energy conversion efficiency increased. The integration of betavoltaics in the microfabricated micropower generators results in a continuous 0.3–0.7 nW power output from the micropower generator ($P_{\text{out,}\beta}$ in Fig. 2.12), in addition to the 12.95 $\mu$W pulsed electrical power output from the piezoelectric thin film ($P_{\text{out,uni}}$ in Fig. 2.12).

Additionally, the basic REMPG fails to take advantage of the radioisotope discharge event to generate wireless RF signals, which has been previously demonstrated in radioisotope actuated dielectric cantilever systems [27] (Fig. 2.13). The discharge event can be harnessed to produce wireless RF signals ($P_{\text{out,RF}}$ in Fig. 2.12) by exciting the LC resonance of the circuit formed by the piezoelectric unimorph cantilever and the electrical components connected across the dielectric insulating the piezoelectric
Figure 2.12: Schematic illustrating the power output profile of the IREMPG

Figure 2.13: Schematic illustrating the generation of wireless RF signals in radioisotope actuated reciprocating dielectric cantilevers, due to (a) build-up of an electric field in the dielectric with charges accumulating on either electrode during the charging phase, and (b) excitation of RF modes in the dielectric waveguide by the displacement current caused by the sudden shorting during discharge.
stack from the silicon cantilever body. Furthermore, the wireless RF signal frequency can be tuned by applying voltage biases across the piezoelectric thin film. This frequency tunability can be used to realize self-powered wireless RF sensors beacons to convey information between wireless sensor and RFID nodes.

### 2.2.5 $^{147}$Pm Micropower Generation

A majority of autonomous microsystems require 100 $\mu$W–100 mW continuous power output from their microbatteries. Therefore, they cannot function with the pulsed electrical power generators fueled by $^{63}$Ni. Microbatteries for such applications require high power density and high energy capacity radioisotope fuels. Thin film $^{147}$Pm is a very suitable fuel for such microbatteries because of its high $P_{g,dens}$ ($\approx$ 2.05 W/cc at 830 curie/g) [28] and long $\tau_{1/2}$ (2.6 years). Even though the $^{147}$Pm maximum radiation energy of 200 keV poses a slightly increased radiation safety risk, $^{147}$Pm powered betavoltaic microbatteries have been proven safe enough to be deployed widely in implantable cardiac pacemakers. Previously developed cardiac pacemaker batteries employing as much as 66 curies of $^{147}$Pm realized low radiation dose rates of 6.1 millirem/h at 2.5 cm [11].

In this book, high efficiency 3D silicon electronvoltaics are developed (Chap. 5) to realize $>5$ mW/cc, 5 year lifetime betavoltaic microbatteries using $\approx$ 100 curies of $^{147}$Pm (Fig. 2.7).

#### $^{147}$Pm-Silicon Betavoltaic Microbatteries

A variety of radioisotope energy conversion mechanisms can be employed for $^{147}$Pm energy conversion. However, betavoltaic energy conversion has proven most efficient for $^{147}$Pm. Primary energy conversion is not suitable because it requires generation and sustenance of impeding voltages equivalent to the average energy of the radiation, and it is difficult to sustain 63 keV across microscale gaps. Heat based engines are not as suitable because they require radioisotope fuels with $P_{g,dens} \approx$10–100 W/cc [1] to sustain the large temperature gradients required for efficient energy conversion.
Radioisotope powered betavoltaic microbatteries operate by irradiating semiconductor p–n junctions with low energy \( \beta \)-radiation to generate electron–hole pairs (EHPs), and collecting the EHPs across the junction to generate electrical power. Betavoltaics are analogous to photovoltaics, where photons are used to generate EHPs near a semiconductor junction. Previous \( ^{147}\text{Pm} \) betavoltaic microbatteries employed planar silicon betavoltaics, and realized 100 \( \mu \text{W/ cc} \) output power densities and 6–8 year lifetimes [11]. Their power densities, given by

\[
P_{\text{out}, \beta, \text{dens}} = P_{r, \text{dens}} \times FFF \times \eta_\beta, \tag{2.5}
\]

were low both because of low radioisotope fuel fill factors \( FFF \) (2\%) and low energy conversion efficiency \( \eta_\beta \) (2\%). The fuel fill factor was low because the \( \beta \)-electron self-absorption in the \( ^{147}\text{Pm} \) thin film limits the maximum thin film thickness to 6 \( \mu \)m for \( \eta_r > 85 \)%. Since the silicon betavoltaics were fabricated on 300 \( \mu \)m thick wafers, \( FFF \) was 6/300 \( \approx \) 2\%. The \( FFF \) can be raised by increasing the radioisotope-betavoltaic interface surface area, and past attempts have included employing KOH etched pyramidal texturing [23], and porous silicon 3D nano-texturing [29] of the betavoltaic surface. However, while KOH etched pyramids give a fuel fill factor enhancement of just 1.85X, porous silicon approaches are not efficiently applicable to \( ^{147}\text{Pm} \) powered silicon betavoltaics, because silicon microstructures need to be > 50 \( \mu \)m thick to absorb > 90\% of the 63 keV \( \beta \)-electrons.

**3D Silicon electronvoltaics for \( ^{147}\text{Pm} \) Microbatteries**

The aforementioned limitations can be overcome by employing DRIE textured 3D betavoltaics that are interleaved and stacked for maximum \( FFF \) (Fig. 2.14). The novel 3D design promises to realize a net power density increase of 14–20X over previous planar betavoltaics, through a 8–10X increase in the fuel fill factor realized by increasing the radioisotope-betavoltaic interface surface area, and a 1.5–2X increase in the conversion efficiency realized by efficiently utilizing the \( \beta \)-electron radiation emitted from both sides of the radioisotope thin film. The resulting betavoltaics can enable smaller microbatteries with useful power output levels, using smaller quantities of radioisotope fuel for lower cost and radia-
Figure 2.14: 3D dimetric view schematics of (a) 3D silicon diodes, (b) two interleaved betavoltaic wafers to be stacked, and (c) assembled 3D betavoltaics
tion dose rate. Furthermore, the 3D design can be readily applied to betavoltaics fabricated using higher band-gap semiconductors such as silicon carbide (SiC), gallium nitride (GaN), and Diamond for even higher conversion efficiencies.

### 2.3 Radioisotope Direct Charged Voltage Biases for Autonomous Sensors

Radioisotopes can be used as high energy density fuels in high energy capacity microbatteries for long lifetime microsystems. However, high power output microbatteries require high activities of radioisotope fuels. This undesirably raises safety concerns, and often limits the use of such microbatteries to specialized applications that can tolerate the lower radiation safety.

Alternatively, radioisotopes can also enable long-lifetime microsystems through their radiation effects. For example, $^{63}$Ni and americium-241 ($^{241}$Am) enable low-power electron capture detectors [9] and smoke detectors respectively by acting as zero-power ionization sources. Such applications can function with very small activities ($<$ 1 millicurie) of radioisotopes. Consequently, such applications may be safe enough to be deployed widely. In this book, another such application for $^{63}$Ni thin films is proposed.

#### 2.3.1 $^{63}$Ni Thin Film Generated Voltage Bias for Self-powered Sensors

The $\beta$-radiation from $<$ 5 millicurie of $^{63}$Ni is used to enable a zero-power wireless sensor microsystem which can transmit a pulsed RF signal coded with the sensed environmental information [30]. The $^{63}$Ni source is used to electrostatically actuate a gold cantilever, and the pull-in triggered discharge is used to generate wireless transmission signals [27]. The frequency of this wireless signal generated is modulated by a humidity sensitive capacitor sensor connected to the cantilever. The humidity sensitive capacitor can be replaced by a capacitor sensitive to any other physical measurand to realize a wireless sensor
micr osystem. The resulting self-powered wireless sensors can function autonomously for decades enabling long-term monitoring of structural and environmental health in remote places.

2.4 Radioisotope Decay Rate based Counting Clock

The rate of radioactive disintegrations (activity) is a constant for a given amount of radioisotope material. The radioisotopes do not age as there are no inherent physical effects that change the rate for a given amount of material. Thus a radioactive source can potentially be used to construct atomic clocks and provide the necessary long-term stability for the clock. This book presents such clocks, called radioactive counting clocks, or simply, counting clocks.
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