Pervasive Power: A Radioisotope-Powered Piezoelectric Generator

A long-lasting radioisotope micropower generator for self-powered sensor microsystems promises to make pervasive computing systems more reliable. Its higher energy conversion efficiency enables microsystems with small amounts of radioactivity to realize sensor and basic computation operations.

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Research on pervasive computing systems has focused on algorithms, system architectures, and software issues associated with systems that compute for extended time periods and that are incorporated into everyday objects. However, as the time period for system use increases, hardware reliability becomes an important design factor. A possible reliability metric for pervasive computing systems could be the degree to which the systems are immune to power loss and wide variations in operating conditions. The goal is to achieve power sources that operate over a wide temperature range and for extended time periods with high reliability.

To reach this goal, researchers have investigated technologies for miniature micropower applications and developed radioisotope power generators (see the "Related Energy Sources" sidebar). Unfortunately, the former usually suffer from low energy densities, low conversion efficiencies, or unreliability, while the latter suffer from low energy conversion efficiencies, taking away from the high energy densities that radioisotope thin films offer. To help remedy this, we've created a power source employing radioactive thin films and piezoelectric unimorphs, using a nonthermal energy conversion cycle that enables much higher energy conversion efficiency.

A potential for power: Radioactive thin films

The kinetic energy of the particles emitted from radioisotopes is temperature insensitive up to fusion temperatures (radioactive thin films emit electrons as beta particles, helium nuclei as alpha particles, and photons as x-rays). This can extend a pervasive computing system's operating temperature range, possibly from milliKelvin to thousands of Kelvin, assuming the hardware is composed of the appropriate materials. Moreover, radioactive thin films emit energy over a time governed by the half-life, which can be very long. For the ^{63}Ni β-source we used, the half-life is 100.2 years. Hence, the power sources we describe could extend a system's operating life by several decades or even a century, during which time the system could gain learned behavior without worrying about the power turning off.

Radioactive thin-film-based power sources also have energy density orders of magnitude higher than chemical-reaction-based energy sources. This enables submillimeter-scale power sources, which is significant given the crucial role that metrics of power and energy density play in determining pervasive computing systems' usefulness in applications limited by size.

For example, although pacemakers and diabetes-monitoring equipment are already available, no system is small enough to fit inside a prostrate or brain for long-term monitoring

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Related Energy Sources

Micropower sources

Researchers have investigated several technologies for miniature micropower applications. The most commonly used electrochemical batteries have very high conversion efficiencies (up to 50 percent) but suffer from low energy densities (1–2 kJ/m^3).[1] Hydrocarbon fuels have higher energy densities (20 kJ/m^3) but suffer from low conversion efficiencies at the microscale. Demonstrated technologies for hydrocarbon energy generation at the microscale conversion include microfuel cells[2] and microheat engines.[3] Solar cells[4] can potentially provide long lifetimes at an acceptable power density (10 mW/cm^2 under direct sunlight) but need light for operation, which might not be available at all times.

Several groups have demonstrated energy harvesting from ambient vibrations, light, and wind, as illustrated by the other articles in this issue. However, the energy and power density for such sources are stochastic variables. Here, we present a piezoelectric power source that uses an energy source that is not stochastic and is available at all times, potentially for several decades. Most significantly, our power source employs piezoelectric elements for energy conversion just like in the vibration energy-scavenging approach. Hence, the mechanism presented here offers to complement vibration energy scavenging by allowing vibrations to generate power when the vibration power is available, while at the same time providing energy from radioactive drive of piezoelectric generators when the vibrations aren't present.

Radiated energy from radioisotopes

Compared to chemical fuels, radioisotopes have very high energy densities (approximately 10^5 kJ/m^3).[5] Additionally, since the half-lives of radioisotope thin films can range from hundreds of years to a few seconds, we could design a power source with the optimal lifetime by choosing a suitable radioisotope.

Early work on radioactive-energy conversion focused on thermal heating using the kinetic energy of emitted particles.[6] The heat can then be converted into electricity using the thermoelectric[7] and thermionic[8] conversion mechanisms. These mechanisms employ heat cycles and require high temperatures (300 to 900 K) for efficient operation. They're generally useful to generate power in the few watts–kilowatts range, but they don't scale down well for micropower applications. As the size reduces, the surface-to-volume ratio of the heat source increases, leading to a higher percentage of heat leaked to surroundings. Although it might be possible to reach high thermoelectric conversion at the microscale using exotic materials and nano-heat-transfer effects, thermal heat energy management at the microscale is a tough engineering challenge.

An alternative to high-efficiency energy conversion is direct charging of capacitors with emitted charged particles from radioactive thin films.[9] These systems generate very high voltages (100 kV to 10 MV), which are necessary for efficient energy conversion. The need for power conditioning circuitry at these voltages makes this approach untenable. Another approach commonly employed for microscale radioactive power sources is using the betavoltaic effect (emitted charge e-h^+ generation),[10] much like in solar cells. Betavoltaic cells tend to be low-power devices operating at low efficiencies (< 0.5 percent). Moreover, they present a trade-off between power output and lifetime because increased radiation doses onto semiconductors can lead to limited lifetime due to impact damage.

REFERENCES

1. J.B. Bates et al., "Rechargeable Solid State Lithium Microbatteries," *Proc. IEEE Micro Electro Mechanical Systems* (MEMS 93), IEEE Press, 1993, pp. 82–86.
2. J.D. Holloday et al., "Microfuel Processor for Use in a Miniature Power Supply," *J. Power Sources*, June 2002, pp. 21–27.
3. V.H. Schmidt et al., *Proc. 6th IEEE Int'l Symp. Applications of Ferroelectrics*, 1986, pp. 538–542.
4. J.F. Randall, *On Ambient Energy Sources for Powering Indoor Electronic Devices*, PhD thesis, EPFL, 2003.
5. W.R. Corliss and D.G. Harvey, *Radioisotopic Power Generation*, Prentice Hall, 1964.
6. C.W. Stephens, *Dynamic Thermal Converters, Energy Conversion Systems Reference Handbook*, vol. 3, 1960.
7. F.B. Brauer et al., US Air Force RADC-TR-56-130, 1956.
8. V.C. Wilson, *Astronautics and Aerospace Eng.*, vol. 1, 1963, p. 62.
9. J.H. Coleman, *Nucleonics*, vol.11, no. 42, 1953.
10. H. Guo et al., "Nanopower Betavoltaic Microbatteries," *Digest of Technical Papers, Transducer 03,* vol. 1, 2003, pp. 36–39.

without external power. In fact, a total system volume of less than a cubic millimeter is inaccessible to current pervasive computing architectures that use batteries. You might argue that computers smaller than one millimeter are more sensors than useful computers, but many commercially viable handheld pervasive computer architectures require input from an array of microautonomous sensors. These sensors also must be reliable so that embedded sensors in the human body, or in buildings, work not only in normal operating conditions but also when the body or building isn't providing power. The sensors should be able to detect a missing component in a building, nonfunctioning body parts, or undesired RF signals from a spy and should continue to log data even when the power for the tra-

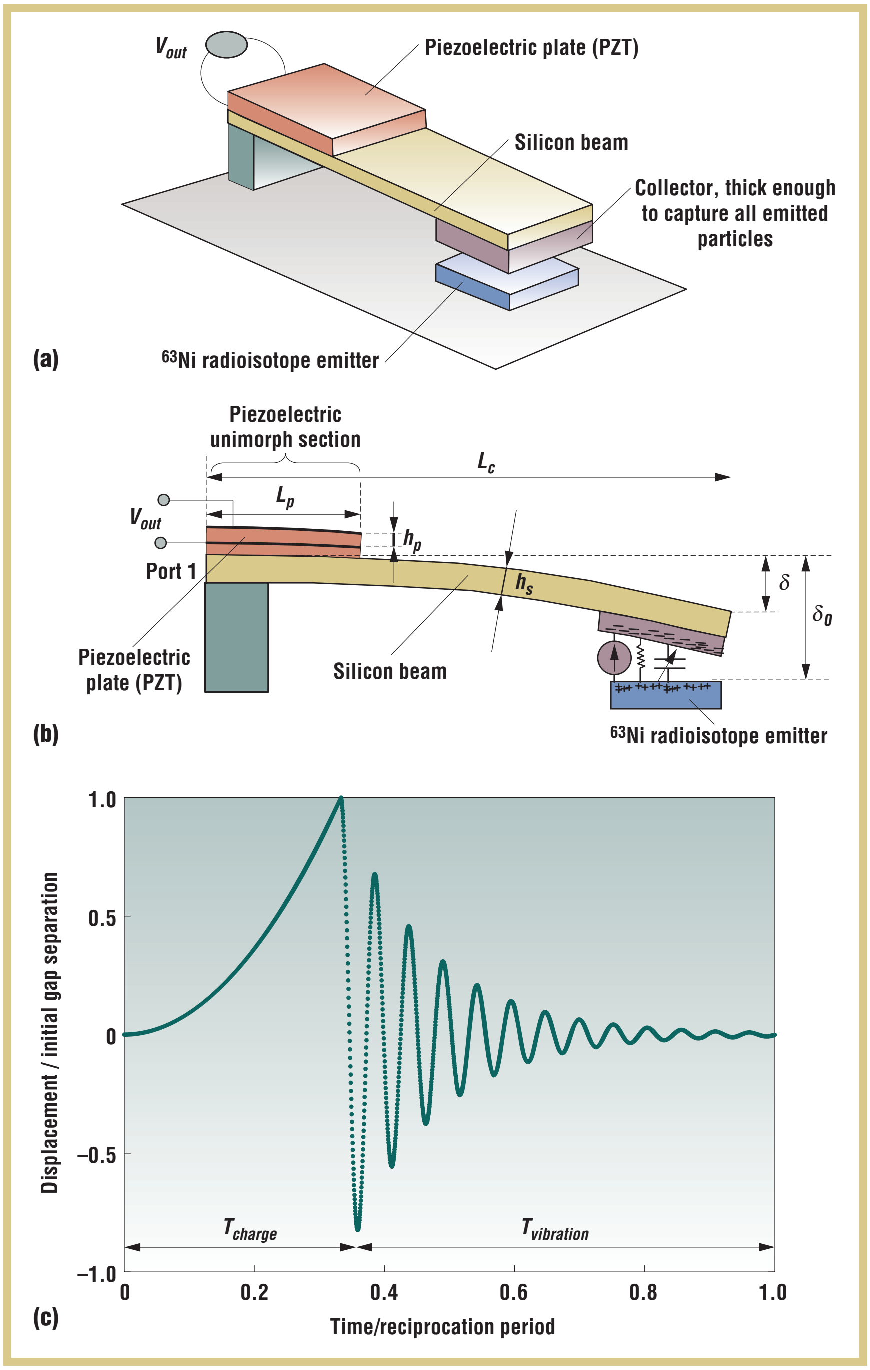

Figure 1. The radioisotope-powered piezoelectric generator's construction and working principle: (a) schematic 3D view; (b) cross-section showing the structure's geometrical parameters and a model of the air-gap capacitor. Emitted charges generate the current source, the resistor is due to ionization current and secondary electron emission, and the source plate and the collector plate form a capacitor. (c) Plot illustrating the displacement of the cantilever's tip in a typical reciprocation cycle.

ditional pervasive computing system is unavailable.

Researchers have known about radioactive thin films' high energy density for some time, but a high conversion-efficiency mechanism has been elusive at the millimeter scale or microscale. We demonstrate power conversion efficiency of emitted nuclear-to-electrical power of two to three percent, using a radioactive-to-mechanical-to-electrical conversion cycle. Given that the energy density of radioactive thin films is 100 to 1,000 times higher than chemical energy density, a volumetric scaling of the electrical energy source of three to 70 is possible. This advantage scales the power source volume to be much smaller, letting us achieve a total pervasive computing volume of sub-one-millimeter cube.

Our radioisotope-powered piezoelectric generator

Our RPG builds on previous work where we reported on a self-reciprocating direct-charging cantilever.[1] We showed the feasibility of capturing the kinetic energy of emitted particles to actuate a cantilever and convert the radiated kinetic energy to stored mechanical energy in the cantilever. Our RPG uses the direct-charging process to actuate a piezoelectric unimorph, which in turn generates electrical power. This is similar to vibration-scavenging converters that use piezoelectric devices.[2,3] The piezoelectric unimorph supplies the load circuit with a directly usable voltage signal while shielding it from the high voltage generated owing to the radioisotope's direct charging.

Construction and working principle

As Figure 1a shows, in our RPG, the collector at the cantilever beam's tip traps the charged particles emitted from the thin-film radioactive source. Through charge conservation, the radioisotope film is left with 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 (see Figure 1b). For suitable initial gap separations, the cantilever's tip eventually makes contact with the radioactive thin film, neutralizing the accumulated charges via charge transfer. As the electrostatic force is reduced to zero, the cantilever is released, exciting cantilever oscillations (see Figure 1c).

The oscillations put stress on the piezoelectric element near the anchor. The time-varying stresses lead to charges induced across the piezoelectric element at the cantilever's base. The piezoelectric element thus behaves as a current source supplying electrical power to any external circuit connected across its terminals.

By applying a suitable load across the RPG, we can design the cantilever system to behave as a resonant power source. We can use the direct AC signal from the micropower generator in a radioactively powered acoustic transmitter for application in wireless sensor nodes.[4] We can also use a rectifier circuit topology to extract power. The micropower generator's rectified output current can charge a storage capacitor or rechargeable battery. We later demonstrate the power of a microsystem comprising an optical sensor that modulates a silicon-on-sapphire ring oscillator for data logging.[5]

By applying a suitable load across the radioisotope-powered piezoelectric generator, we can design the cantilever system to behave as a resonant power source.

Device analysis

Here we present an elementary analysis of the RPG device. (We present its design, fabrication, and power generation characteristics in detail elsewhere.[6]) For the purpose of analysis, we assume a simple resistor load focuses on the microgenerator's characteristics. 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 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 devices with high efficiency, because high charge voltages requiring long reciprocation times lead to high efficiency. We can calculate the charging period T_{ch} using

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

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 piezoelectric element's capacitance. For the devices discussed here, E_m is approximately 1,000 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 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. We can maximize the ratio η_r by designing the peak charging voltage of the air-gap capacitor $V_{cap\max}$ to satisfy the following condition:

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

Equation 6 is based on the two simplifying assumptions that the peak charging voltage isn't limited by voltage breakdown in the gap and that all the emitted particles have a kinetic energy of E_{avg}. However, in reality, gas breakdown limits the maximum voltage built-up across the gap.[6] This in turn affects the level of efficiency we can achieve.

Regardless of the radioisotope element's beam stiffness and activity level, which can remain constant, the cantilevers' reciprocation period can be short (100 ms) or long (1 hour), depending on the initial gap separation. The larger the initial gap separation, the higher the cantilever's final mechanical energy, resulting in more available power. By carefully optimizing the structure, we've demonstrated an overall conversion efficiency of 2.78 percent. The optimized generator goes through a charge-discharge-vibrate cycle, integrating all the energy collected during the charging phase (115 min. at 48 nW input energy from a weak 0.5 milliCurie

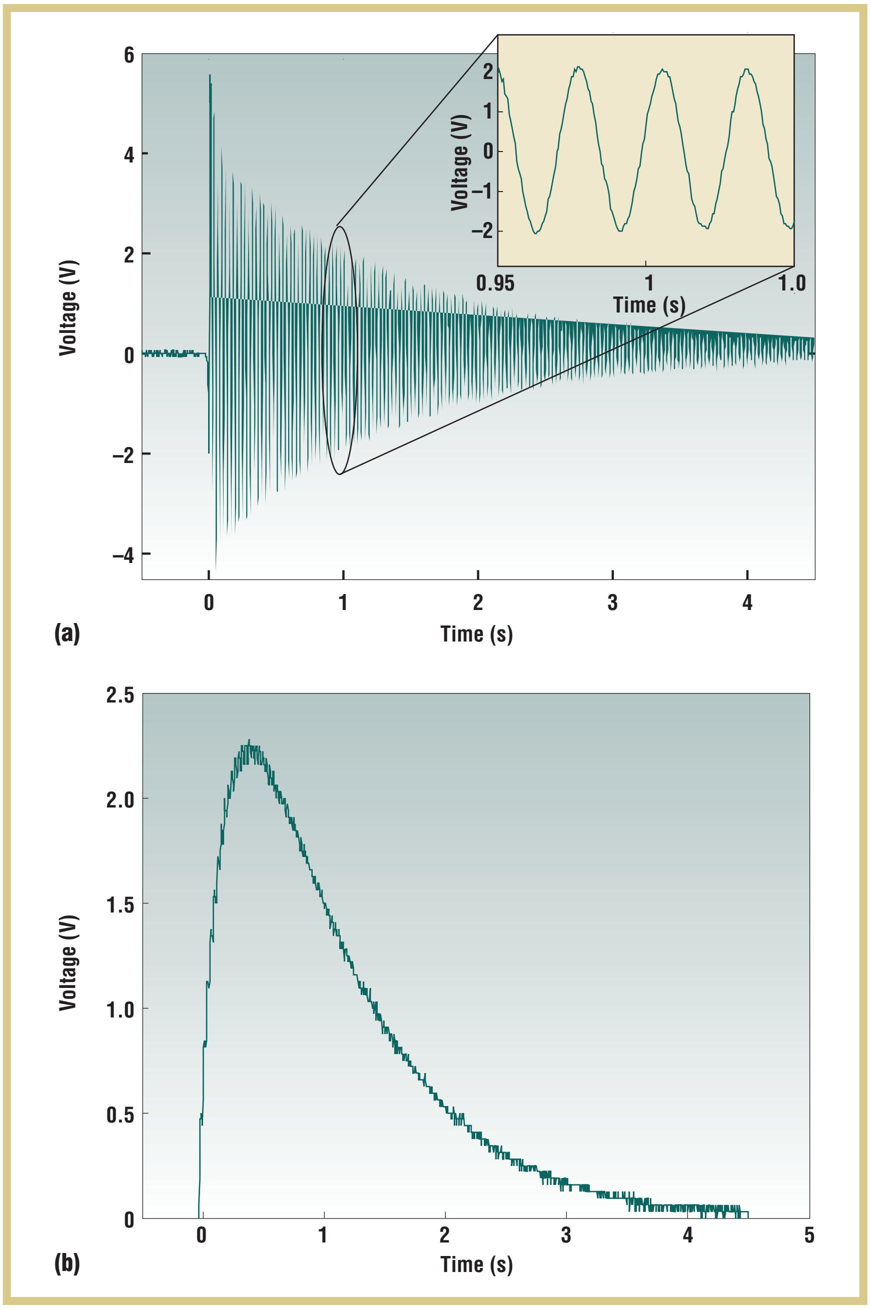

Figure 2. Cantilever oscillations: (a) measured voltage characteristics of the microgenerator after discharge, across a 1 M load; (b) measured voltage across a storage capacitor charged up by the rectified current from the micropower generator.

source, resulting in a total energy input E_r of 331.2 µJ per cycle). This enables high power output (16 µW peak across a 1 MΩ load impedance, calculated from the measured voltage and Equation 4) for a short time (7 s) during the vibration cycle, resulting in a total energy output E_{ext} of 9.2 µJ per cycle. We calculate the device's efficiency from Equation 5.

Further increasing power output

We can achieve higher average power output by increasing the radioisotope's activity (activities are approximately hundreds of milliCuries), which reduces reciprocation time (see Equation 2). In some cases, this can even lead to continuous reciprocation, with average power output in the tens of µW range, which could power low-power electronics or trickle-charge a battery.

We can also use the AC signal from the piezoelectric element either directly or rectified to charge an external capacitor. The resulting voltage bias (approximately 2 V) could drive low-power sensors and electronics. Figure 2a shows the power generation characteristics of the RPG used in the sensor microsystem we describe later. The oscillation frequency is 35 Hz, and the peak output power is 30 µW at an overall conversion efficiency of 1 percent. A close-up of the waveform at $t = 1$ s from the discharge shows the oscillations' sinusoidal nature. Figure 2b shows the measured rectified voltage across a 470 nF external capacitor. The capacitor is discharged in three seconds in the graph owing to the oscilloscope's loading (which is approximately µA).

By trading continuous power for pulsed power, high power is possible even with low-activity radioactive sources, mitigating the safety issues associated with large amounts of radioactive thin film (see the "Radioactive Power Sources: Safety and Societal Implications" sidebar). The power source behaves much like a firefly, where the power is available periodically, and it can be used over the rest of reciprocation time. This power source is also somewhat analogous to the shoe-generated power supply,[7] where each footstep enables power generation.

Of the three radiation types (α-particle, β-particle, and γ-ray), β-particle emission is favorable for efficient conversion owing to the lower energy/charge ratio of the β-particles. The emitted particles, once absorbed in the cantilever, contribute to the energy conversion only through their residual charge (see Equation 2), with their kinetic energy dissipating as heat. The emitted particles' energy content determines the maximum allowable built-up electric field in the gap (Equation 6), which in turn determines the maximum initial gap separation that can sustain reciprocation and hence the maximum mechanical energy stored in the unimorph system (see Equation 3). We can't use γ-ray emitters because the thin layers of materials typical of microsystems can't absorb them. More importantly, radioisotopes emitting γ-radiation pose a safety hazard because of the difficulty in confinement.

A prototype pervasive sensor system

Here we demonstrate a prototypical sensor system, powered by our RPG. We power an optical receiver interfaced with a voltage-controlled oscillator using the RPG. At the simplest level, such a system could serve as a light detector that also maintains an event log.

We custom designed the ring oscillator for low-power (1 nW), low-voltage (0.7 V) operation using long-channel transistors in the ultralow parasitics 0.5 μm silicon-on-sapphire CMOS (complementary metal-oxide semiconductor) process. The ring oscillator consists of five stages with a tail current source to control the circuit's power consumption. The current source is biased using a diode stack between the oscillator power rail (Vdd) and ground rail (GND). We modified the ring oscillator's first and last inverter stages to accommodate the output buffer's load and optimize the oscillator's speed-energy performance. Figure 3 shows the ring oscillator's current-voltage (I-V) characteristics and the oscillation frequency's bias voltage dependence. We used a commercial off-the-shelf silicon p-i-n photodiode as the light detector. The photodiode has a responsivity of 0.5 A/W, an active area

Radioactive Power Sources: Safety and Societal Implications

When dealing with radioactive materials or systems that employ radioactive materials, safety is a major concern, not only from the possibility of actually having a health-safety issue but also the degree to which society is psychologically sensitized to anything radioactive. The ultimate success of radioisotope-powered piezoelectric generators will depend on offering a feature that offsets any safety issue. For example, if an RPG-powered system can warn early in the event of a stroke or heart attack, or against a terrorist or environmental disaster, the relatively smaller risk from minute amounts of radioactive thin film presence would be acceptable. Consider the prevalence of radioluminescent "EXIT" signs. These signs contain significant amounts of radioactive tritium (10 Curies), but they're readily found in public buildings such as schools and hospitals, because they reduce risk of accidents from a more commonly occurring power outage.

Another safety concern with radioactive thin films is the possibility of a terrorist using them to create a "dirty bomb." This risk can be mitigated by realizing submillimeter-cube pervasive computing systems that use small amounts of radioactivity, forcing a potential terrorist to work very hard to accumulate enough material.

Regarding safety issues specific to our power generator, it's powered by a 16 mm^2 thin film (10 micron thick) of ^{63}Ni radioisotope with an activity level of 0.5 milliCurie (1 Curie = 3.7×10^{10} disintegrations/second), which is negligible compared to the 10 Curies of tritium typically used in modern emergency exit signs. Furthermore, ^{63}Ni emits a very-low-energy β-radiation (17 keV average energy as compared to a few MeVs for some α-particles), which has a very low penetration depth (20 microns in most solids). In fact, they are also blocked by the thin layer of dead skin covering our bodies. 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 RPG for microsystems such as remote sensor nodes. The element nickel isn't highly toxic, as opposed to many other kinds of radioisotope elements, reducing risk of chemical toxicity.

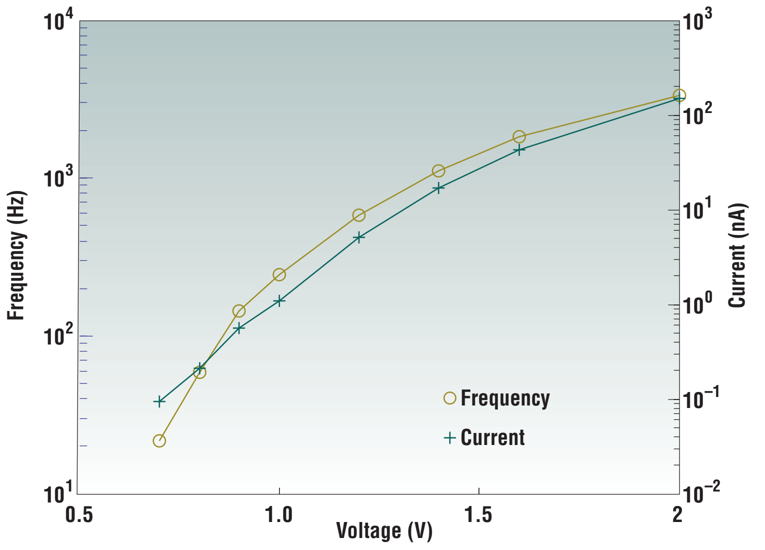

Figure 3. The ring oscillator's measured oscillation-frequency dependencies and input current on voltage bias.

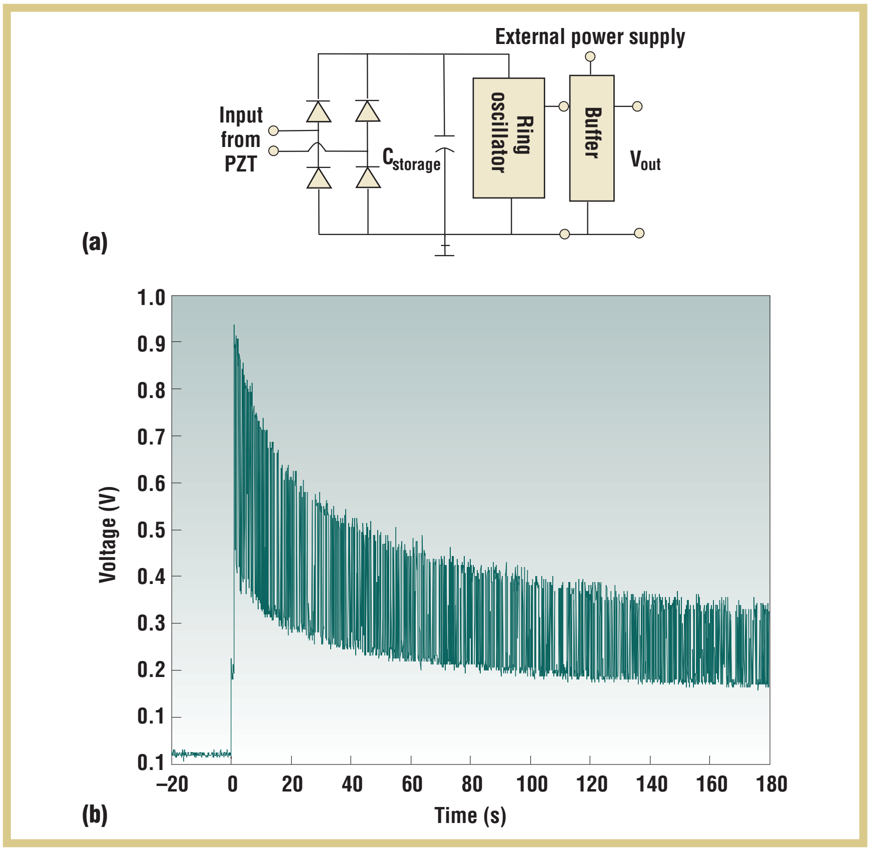

Figure 4. (a) Schematic of the ring oscillator powered by the rectified signal from the RPG; (b) the measured output of the ring oscillator at the end of a reciprocation cycle. The oscillations lasted six minutes (amplitude >50 mV). The frequency was stable to 20 percent from 180 sec. to 240 sec. The ring oscillator output decay follows the bias output decay (see Figure 2a). $t = 0$ corresponds to the time when the cantilever discharges and starts oscillating.

of 13 mm^2, a dark current of 10 nA, a spectral response of 350-1,100 nm, and a diode capacitance of 20 pF. We used a 780 nm vertical cavity surface emitting laser (VCSEL) as a light source to test the sensor microsystem.

The micropower generator's rectified output signal (Figure 2b) charges a storage capacitor, thus generating a bias for driving the low-power ring oscillator (see Figure 4) or a photodiode (see Figure 5). The photodiode output current for an incident optical power of 500 nW at 780 nm is 250 nA, and the ring oscillator oscillates at 1.58 kHz for an input bias current of 250 nA at 1.4 V. Recognizing this, we connected the ring oscillator at the photodiode output and shone a square wave modulated VCSEL laser beam on the photodiode. Figure 6 shows the ring oscillator's resulting modulation. We could readily use the sensor microsystem in light-sensing applications because the ring oscillator shuts off in the light-off state, and the frequency of oscillation in the light-on state depends on the incident light's intensity.

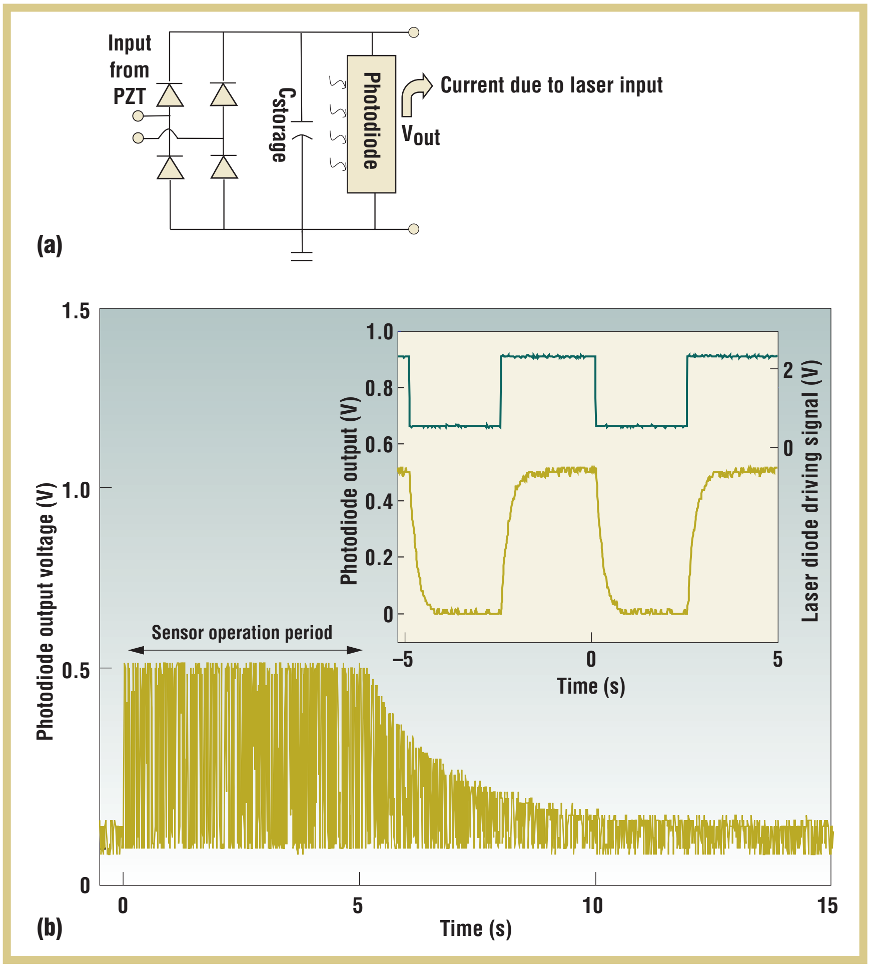

Figure 5. (a) Schematic of the photodiode driven by the micropower generator and sensing an input from a pulse-modulated laser; (b) the measured output (incident optical power is approximately 250 nW at 780 nm). Close-up measured at $t = 3$ s from discharge. The photodiode works for 0.5 s, when the bias (provided by the RPG) on the storage capacitor falls below 0.5 V, after which the photodiode output follows the bias on the capacitor. Inset shows the photodiode's response to the laser input.

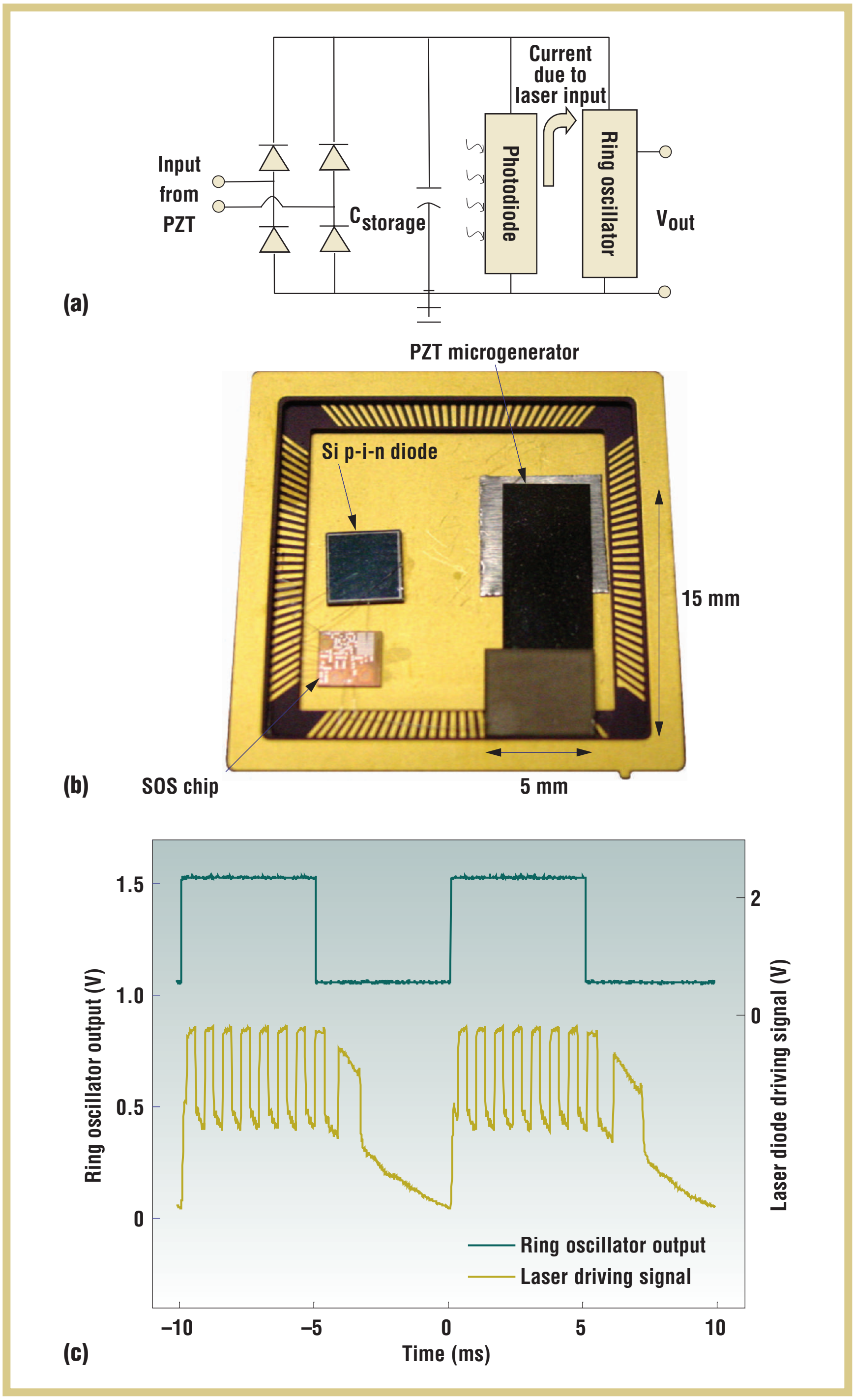

Figure 6. The ring oscillator's modulation: (a) schematic of the optical sensor microsystem; (b) photograph of a prototype optical sensor; (c) measured output from the ring oscillator driven by the photodiode sensing an optical signal from a pulse modulated laser (incident optical power is approximately 500 nW at 780 nm). The ring oscillator's frequency is 1.58 kHz. The waveform was captured 200 ms after the discharge.

Note that the bias for the oscillator is provided by the output of the p-i-n diode, which in turn is biased by the RPG. Shining the laser on the photodiode without connecting it to the RPG won't have any effect on the circuit, as a p-i-n junction behaves as a photodiode only when reverse biased. This demonstrates the ability to power a simple sensor system. It's easy to imagine the integration of a low-power memory system to record light intensity rather than drive an oscillator.

The efficiency level we've demonstrated readily enables power sources with much higher energy density than chemical batteries or fuel cells. For example, even with a prototype package, our RPG has already attained available energy density levels of 5.9 J/cm^3 (assuming a 100 nW output from the ^{63}Ni source for 100 years and a 2.5 percent conversion efficiency, and device dimensions of 2 cm × 1 cm × 0.5 cm), as compared to 0.435 J/cm^3 of a Panasonic Li-ion battery (model CGR1850A, assuming 2,000 mAh capacity and dimensions of 1.8 cm diameter and 6.5 cm height). Furthermore, the chemical battery has a limited shelf life (three to four years) owing to self-discharging across potential barriers. In contrast, the RPG shelf-life-limiting mechanisms may include radioactive thin-film surface degradation or vacuum degradation.

However, the high energy of the electrons has been demonstrated to self-pump chambers and self-clean the surfaces in the battery. These features indicate that the RPG might be the only power source suited for long-lifetime applications without shelf degradation. Although we've presented results for a relatively large RPG, the device architecture is readily scaled to microscale and is particularly amenable to MEMS (microelectromechnical systems). We intend to miniaturize the microgenerator by scaling down the cantilevers and making large arrays of RPGs for different voltage and power levels required by multifunctional microsystems. The physics of breakdown at the microgap level is different and can sustain much higher breakdown fields, a topic we're currently investigating.

We also hope to eventually integrate vibration scavenging and RPG operation to provide enough power for low-power data maintenance operations. Furthermore, the presence of large vibrations could enable higher-power operations from the same baseline architecture.

Needless to say, the RPG offers a unique, long-lasting power source for objects that can't be connected by wires. ▣

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REFERENCES

1. H. Li et al., "Self-Reciprocating Radioisotope-Powered Cantilever," *J. Applied Physics,* vol. 92, no. 2, 2002, pp. 1122–1127.

2. G.W. Taylor et al., "The Energy Harvesting Eel: A Small Subsurface Ocean/River Power Generator," *IEEE J. Oceanic Eng.*, vol. 26, no. 4, 2001, pp. 539–547.

3. J. Kymissis et al., "Parasitic Power Harvesting in Shoes," *Proc. 2nd Int'l Symp. Wearable Computers*, IEEE CS Press, 1998, pp. 132–139.

4. R. Duggirala, H. Li, and A. Lal, "An Autonomous Self-Powered Acoustic Transmitter Using Radioactive Thin Films," *Proc. IEEE Int'l Ultrasonics, Ferroelectrics, and Frequency Control Conf.* (UFFC 04), 2004.

5. R. Duggirala et al., "Radioisotope Micropower Generator for CMOS Self-Powered Sensor Microsystems," *Technical Digest* (PowerMEMS 04), 2004.

6. R. Duggirala, H. Li, and A. Lal, "An Ultra High Efficiency Piezoelectric Direct Charging Radioisotope Micropower Generator," *Technical Digest*, Hilton Head 04, 2004, p. 137.

7. N.S. Shenck and J.A. Paradiso, "Energy Scavenging with Shoe Mounted Piezoelectrics," *IEEE Micro*, vol. 21, no. 3, 2001, pp. 30–42.

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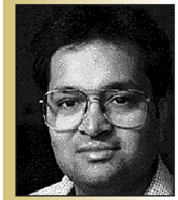

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