BETAVOLTAIC power sources

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A decades-old technology for producing low-level electric current has experienced a recent resurgence in interest and potential applications.

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Low-power, mobile electronic devices are becoming increasingly widespread, and they all need to be supplied with electricity. In large part, lithium-ion and similar batteries are well suited to the task. But the Achilles' heel of those conventional chemical batteries is their limited longevity: The batteries must frequently be recharged and replaced, and they cannot operate at extreme temperatures. Recent advances have positioned betavoltaic batteries to respond to that weakness.

Betavoltaic power sources store energy in a beta-emitting radioisotope; that energy is converted to electricity when the beta particles interact with a semiconductor p–n junction to create electron–hole pairs that are drawn off as current. In that way, betavoltaics and photovoltaics can be considered close cousins. Betavoltaic devices can operate continuously for years or even decades—depending on the half-life of the beta source—even under extreme temperatures (−50 °C to 150 °C) at which chemical batteries fail. They offer advantages under conditions that render battery replacement difficult, impossible, or life threatening, or when long-lasting, continuous, low-power sources are crucial to device operation. In this article we discuss the history, principles of operation, and applications of betavoltaics.

Historical review

Both betavoltaic and modern photovoltaic technologies owe their inception to Paul Rappaport's 1953 work at RCA.[1] He and his colleagues coupled an alloy of the beta-emitting isotopes strontium-90 and yttrium-90 to silicon and other semiconductor junctions to generate power. Their Si-based device converted 0.2% of the incident beta flux into electricity, but the semiconductors degraded quickly, apparently due to radiation damage: It turns out that the beta particles emitted by ^{90}Sr and ^{90}Y were energetic enough to displace atoms in a crystalline solid. From 1953 to 1956, the RCA researchers continued their betavoltaic investigations, using ^{90}Sr, ^{90}Y, and also promethium-147, whose beta particles are less energetic.[2] But their focus gradually turned toward the development of Si and gallium arsenide devices for solar-cell applications.

From 1968 to 1974, one of us (Olsen) led a group at Donald W. Douglas Laboratories, a subsidiary of McDonnell Douglas Corp, to develop betavoltaic

Beta source candidates

Isotope	Beta energy (keV) average	Beta energy (keV) maximum	Half-life (yr)	Price
Tritium	5.7	18	12.3	~$3.50/curie
Nickel-63	18	67	92	~$4000/curie
Promethium-147	62	225	2.6	N/A

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power sources.[3] Our design, stacked layers of Si cells coupled to ^{147}Pm in the form of Pm_2O_3, resulted in the first betavoltaic power source, the Betacel, licensed for use in cardiac pacemakers. The device is shown schematically in figure 1.

The Betacel achieved an efficiency of 4% based on the incident beta flux, and it was able to produce up to 400 μW of power at the beginning of its 10-year useful life. Much of the battery volume was required for shielding the gamma radiation emitted from the ^{146}Pm contaminant in the ^{147}Pm. That drawback, and the high cost and limited availability of ^{147}Pm, meant that once lithium batteries became available, the Betacel could no longer compete. Pacemakers powered by Betacel batteries were implanted in more than 100 patients before the program was terminated.[4]

From 1975 until 2006, studies of betavoltaics proceeded sporadically.[5–8] Researchers examined several different beta sources and semiconductor substrates, but their efforts yielded limited results in terms of power and efficiency. Improving efficiency is important in betavoltaic design because of the high cost of materials and manufacturing, limits on the volume or weight of a device, and—crucially—regulatory restrictions on the amount of radioactive material used.

In recent years interest in betavoltaic technology has returned, according to a 2008 survey by Lockheed Martin. The survey examined the power and energy densities of betavoltaic cells from several manufacturers, including BetaBatt, City Labs, Qynergy, and Widetronix.

Also in 2008 the US Nuclear Regulatory Commission awarded a specific license to Qynergy's QynCell KRT-2000 betavoltaic power cell. A specific license means that the device can be sold to users who are suitably trained to work with radioactive materials. In 2010, City Labs' NanoTritium battery was awarded the betavoltaic industry's first (and so far, its only) general license for manufacturing and distribution, meaning it can be purchased by any user.

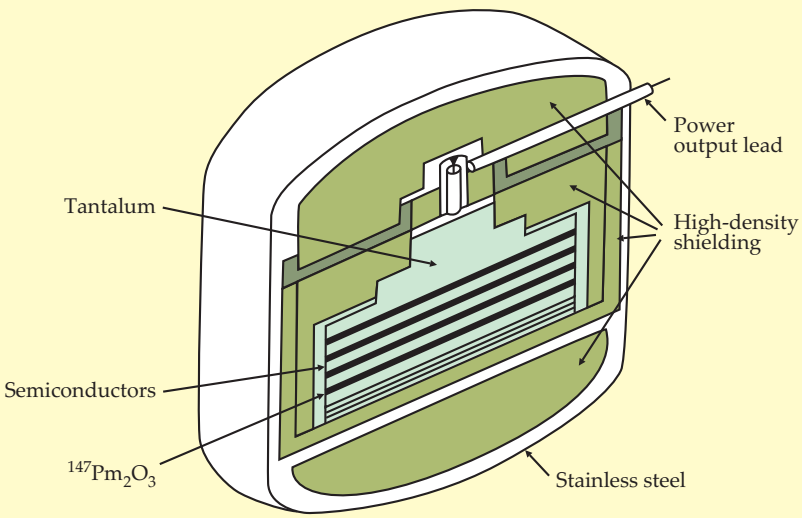

Figure 1. The Betacel model 400, an early betavoltaic battery powered by promethium-147. The device was produced for use in cardiac pacemakers.

Betavoltaics versus photovoltaics

A convenient starting point for understanding how a betavoltaic cell works is to compare it with the more familiar photovoltaic cell. Both technologies involve the generation of electron–hole pairs in a semiconductor, either by solar (or other) photons or by high-energy beta particles. Both produce electric current from the semiconductor p–n junction's built-in electric field acting on the electrons and holes. But the similarities end there.

As shown in figure 2a, a sufficiently energetic solar photon excites an electron from a valence-band energy level to a conduction-band level. Some of the photon's energy, equal to the semiconductor bandgap E_g, goes toward forming an electron–hole pair, and the remainder is lost as low-frequency phonons, or lattice vibrations. A single photon almost never generates two electron–hole pairs, even if it has enough energy to do so. The solar spectrum mainly comprises photons with energies less than 3.5 eV, the same order of magnitude as a typical semiconductor bandgap. By assuming that every photon with energy greater than E_g produces one electron–hole pair with energy E_g, one can derive the Shockley–Queisser limit for the efficiency of a single-bandgap solar cell. That limit is optimized at 33% by a bandgap coincidentally close to that of Si (1.1 eV). (For more on photovoltaics, see the article by George Crabtree and Nathan Lewis, PHYSICS TODAY, March 2007, page 37.)

On the other hand, beta particles typically have energies of tens to hundreds of keV, depending on the radioisotope. Fortunately, as shown in figure 2b, one energetic beta particle can create many electron–hole pairs. Still, much of its energy is lost, as both high-frequency (optical) and low-frequency (acoustic) phonons. Claude Klein showed empirically that when a beta particle creates an electron–hole pair of energy E_g, the average energy it gives up is $2.8\,E_g + 0.5$ eV, with $1.8\,E_g$ lost to acoustic phonons and 0.5 eV lost to optical phonons.[9] That relationship—which implies that the larger the bandgap, the greater the possible efficiency—caps betavoltaic efficiency at around 35% in the limit of large-bandgap semiconductors.

But the flux of solar photons is millions of times greater than the flux of beta particles from a typical beta source. Even accounting for the fact that each beta particle produces many electron–hole pairs, the currents produced in betavoltaic cells are orders of magnitude smaller than those produced in solar cells: nanoamps or microamps per square centimeter, as opposed to milliamps. That difference limits betavoltaic batteries to applications in which low currents are required. It also means that so-called

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dark currents claim a greater fraction of the total current produced by the cell.

If the semiconductor portion of a betavoltaic cell is thought of as a constant-current source in parallel with a diode, the dark current is the current flowing the "wrong" way through the diode; equivalently, it's a reduction in the current flowing the "right" way through the cell. It arises because mid-gap states, due in part to defects in the semiconductor, induce electron–hole pairs to recombine. Creating a semiconductor junction with a sufficiently low dark current is more of a challenge for some semiconductors than for others. For example, silicon carbide, with its bandgap of 3.3 eV, should be an ideal choice for a betavoltaic device, according to Klein's formula. But growing SiC junctions that are large enough (say, 1 cm^2) and sufficiently free of defects has thus far proved to be extremely difficult. As a result, betavoltaics researchers have focused on III–V compounds, such as gallium arsenide, aluminum gallium arsenide, and gallium phosphide, which have smaller bandgaps but can be fabricated as essentially crystalline films.

Choosing a beta source

Many radioisotopes emit beta particles. However, most of them do so with energy spectra that extend beyond 300 keV, the approximate energy required for a beta particle to displace an atom in the semiconductor material. Atomic displacement results in defects that increase the dark current and degrade the betavoltaic cell's performance.[10]

Tritium, nickel-63, and ^{147}Pm are the only three beta-emitting radioisotopes whose maximum beta energy is less than 300 keV and whose half-life is sufficiently long to facilitate a long-life power source. Their properties are summarized in the table on page 35. Although ^{147}Pm was the beta source of choice for the Betacel and can produce a relatively high power density, it is not currently available for purchase in the US. Tritium and ^{63}Ni sources produce similar, lower power—provided that enriched ^{63}Ni is used—but the cost and availability of enriched ^{63}Ni are prohibitive. Furthermore, tritium is ideal from a safety and regulatory perspective: Its weak beta particles cannot penetrate a thin sheet of paper or travel more than 5 mm in air (although they can still generate hundreds of electron–hole pairs in a typical semiconductor). For all those reasons, tritium has emerged as the beta source of choice for betavoltaic devices.

Elemental tritium, an isotope of hydrogen, is a gas, which poses problems of safety and practicality. So researchers have sought ways to store it in a solid matrix. The most promising approach is to use tritides (the analogue of hydrides) of metals such as titanium and scandium. Metal tritides have been used in the past in neutron generators and electron-capture detectors, and Ti and Sc are known for their propensity to absorb and reliably store tritium under the right conditions. The beta flux emanating from metal tritides is limited by their own self-shielding: Tritium betas are absorbed in less than a micron of Sc or Ti. But that problem can largely be solved by stacking thin alternating layers of metal tritide and semiconductor in the desired geometry. That approach allows for a higher energy density for a tritium betavoltaic without the concerns associated with gaseous tritium, especially at high pressures. Assuming a

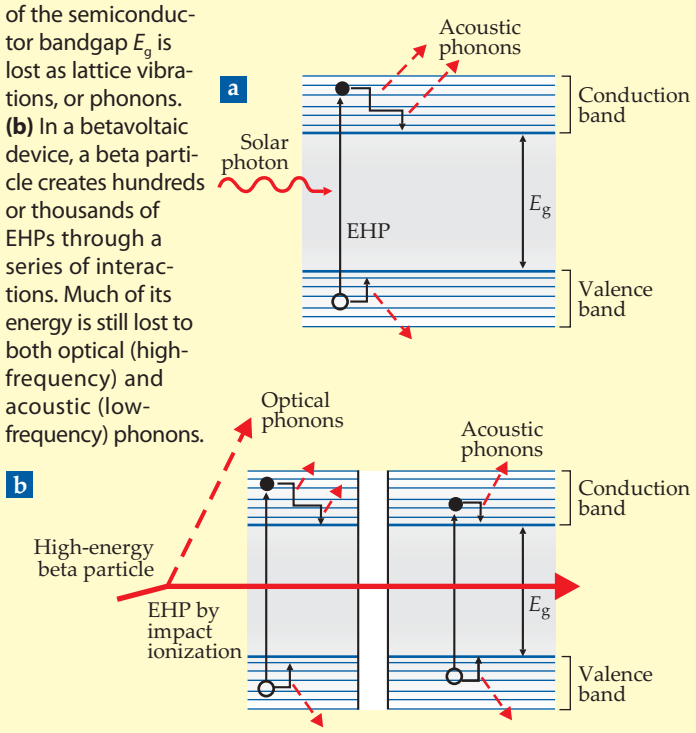

Figure 2. Photovoltaics and betavoltaics. (a) In a photovoltaic solar cell, a sufficiently energetic solar photon creates an electron–hole pair (EHP) in a semiconductor by exciting an electron from the valence band to the conduction band. Any photon energy in excess of the semiconductor bandgap E_g is lost as lattice vibrations, or phonons. **(b)** In a betavoltaic device, a beta particle creates hundreds or thousands of EHPs through a series of interactions. Much of its energy is still lost to both optical (high-frequency) and acoustic (low-frequency) phonons.

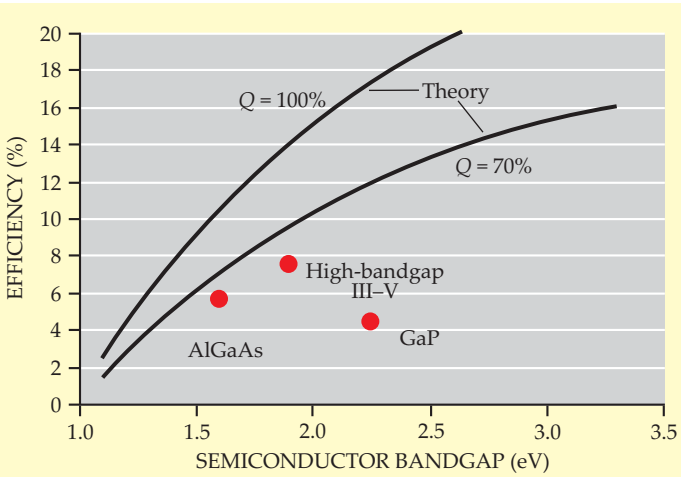

Figure 3. Some recent efficiency measurements for tritium betavoltaics using aluminum gallium arsenide,[5] gallium phosphide,[7] and a high-bandgap III–V semiconductor,[11] compared with the theoretical maximum efficiency as a function of bandgap. Theoretical curves are shown for collection efficiencies Q (the current generated relative to the maximum possible current) of 100% and 70%.

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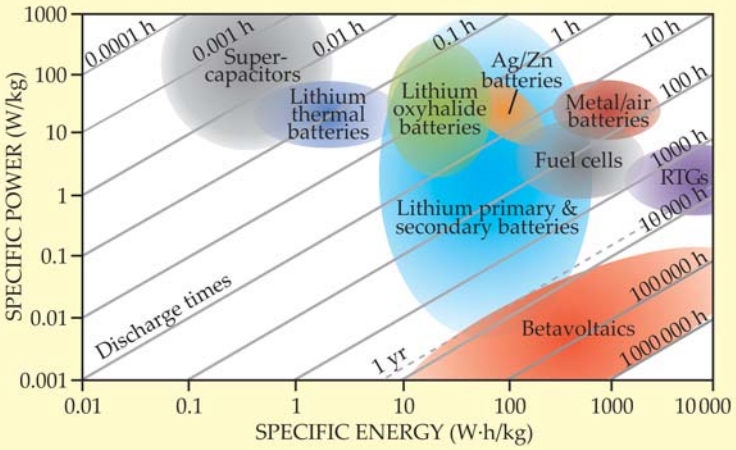

Figure 4. Betavoltaics supply low power over a long lifetime, making them unique among energy-storage devices, including chemical batteries, fuel cells, supercapacitors, and radioisotope thermoelectric generators. RTGs use more aggressive radioisotopes, such as polonium-210 or plutonium-238, to generate heat, which is then converted into electricity via the Seebeck effect. (For more on chemical batteries and supercapacitors, see the article by Héctor Abruña, Yasuyuki Kiya, and Jay Henderson in PHYSICS TODAY, December 2008, page 43.)

semiconductor with 10% conversion efficiency, a tritium gas–based betavoltaic with a 1-cm^3 volume at 3 atmospheres would produce 8.4 μW of power. (Higher pressures would not yield higher power because of self-absorption of betas in the tritium gas.) A device of the same size consisting of layers of titanium tritide deposited on thin semiconductors would yield more than 20 μW.

Another possibility being investigated by some researchers is to store tritium in a liquid or solid polymer matrix. Although the tritium density in a polymer can be higher than in a metal tritide, the stability of the polymer material still needs further research, especially in the areas of isotopic exchange and polymer degradation.

Prospects for achieving tritium-fueled betavoltaic power sources with efficiencies upwards of 10% are good. Figure 3 shows some recent experimental results for efficiency compared with the theoretical limit. Theoretical curves are shown for collection efficiency Q (the current produced as a fraction of the maximum possible current) of 100% and the more reasonable value of 70%, which accounts for the reflection of incident beta particles from the semiconductor surface. We expect that further development of semiconductor devices with low dark currents will allow tritium betavoltaics to approach the $Q = 70\%$ line.

Applications

As shown in figure 4, betavoltaics fill a unique niche among energy-storage devices. Their distinguishing feature is their longevity, but in addition, the energy density of a tritium- or ^{147}Pm-powered betavoltaic battery can be many times greater than that of a lithium battery.

In the defense market, tritium-based betavoltaics are already being introduced to power the encryption keys in field-programmable gate arrays. Although their power requirements are quite low (150 nW), the arrays tend to experience extreme temperatures that can cause chemical batteries to fail. Now that a betavoltaic device has received a regulatory general license, which makes it easily available to the end user who does not have a radiation license or safety training, a range of new applications becomes possible.

A betavoltaic device trickle charging a secondary battery or capacitor can provide burst power—in the range of milliwatts to watts—for critical device operations such as wireless communications. For instance, a betavoltaic-powered sensor and communications system in the desert or tundra can provide measurements and wireless reporting for more than 20 years. And in the extreme conditions under the ocean, betavoltaic-powered sensors monitoring the structural health of the drilling components may even prevent the next deep-water drilling disaster.

Implanted medical devices are a natural application for betavoltaic power sources, whose long lifespans can help minimize trauma to patients. We may see the return of betavoltaic-powered cardiac pacemakers; other possibilities include defibrillators, cerebral neurostimulators, cochlear implants, intraocular implants, brain–computer interface devices, and implanted electronic medical identification tags. Integrated circuit chips measuring 1 mm on a side already feature pressure sensors that can be implanted transdermally to measure the regrowth of a tumor. However, today's small-scale chemical batteries can provide power for only a few months at best. Betavoltaic batteries could provide continuous power for years or even decades.

The high energy density found in betavoltaic batteries enables a diverse range of low-power, long-term microelectronic device applications that were previously not possible or simply unexplored until now.

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