BETAVOLTAIC PERFORMANCE UNDER EXTREME TEMPERATURES

by

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Longevity of sensors and portable devices is severely limited by temperature, chemical instability, and electrolyte leakage issues associated with conventional electrochemical batteries. Betavoltaics, which operate similar to photo voltaics, can operate in a wide temperature range safely without permanent degradation. Though not a new concept, which began in the 1950's and peaked in the mid 1970's, research has been minimal and sporadic until recent advancements in ultra-low power electronics and materialization of low power applications. The technology is rapidly maturing, generating research, and development in increasing the beta emitting source and semiconductor efficiencies. This study presents an update on betavoltaic technology, results from temperature evaluation on commercially available General Licensed betavoltaic cells, development of a hybrid system for latent and burst power, modeling and simulation techniques and results, and current and proposed research and development. Betavoltaic performance was successfully demonstrated for a wide temperature range (–30 °C to 70 °C). Short circuit current and open circuit voltage were used to compare electrical performance. Results indicate that the open-circuit voltage and maximum power decreased as temperature increased due to increases in the semiconductor's intrinsic carrier concentration.

Key words: betavoltaic, radioisotope power source, energy harvesting, hybrid battery, solid-state battery, beta emitter, p-n junction, latent power, low power, modelling

INTRODUCTION

Radiation interaction with materials can have beneficial uses, such as in betavoltaic cells, a type of radioisotope power source where the kinetic energy associated with beta (β^-) decay is converted into electricity. Though not a new concept, research and development has been minimal for many years due to limited low-power applications, rapid semiconductor degradation, limited availability and high cost of suitable radioisotopes, and public perception. Novel and compelling need-based applications are emerging in the military, intelligence, commercial, and medical markets that can utilize the diminutive energy produced from such cells. Present-day micro-electromechanical systems and electronic devices make betavoltaics an attractive alternative to electrochemical batteries enabling applications to perform for much longer periods in extreme temperatures. Unlike conventional electrochemical batteries, commercially available betavoltaics can operate in excess of 10 years over temperatures ranging from –55 °C to 150 °C [1]. Since the technology is far from mature, many challenges and issues remain to be solved to improve efficiency and energy density, and reduce cost, which will be discussed in the background section of this paper.

Little performance and aging data exists on current betavoltaic technology. Furthermore, temperature behavior data are not known. Betavoltaics made by City Labs are being evaluated under temperature and other external forces such at electric fields, magnetic fields and high energy radiation in the form of neutrons and gamma rays. The results will provide a benchmark for inserting betavoltaics into applications.

Radioisotopes are encountered by everyone daily and are used safely in many locations, such as households, hospitals, retail stores, and aircraft. For example, smoke detectors rely on americium-241 for sensing smoke. Hospitals use radiographic imaging devices and tracers in many of their treatment protocols. Tritium is used in many products, such as exit signs, gun sights, and watches to provide illumination. Promethium-147 (^{147}Pm), a byproduct of nuclear fission, has been used to illuminate gauges for aircraft.

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Before these devices become available, a Sealed Source & Device Registration (SSDR) is required from the U.S. Nuclear Regulatory Commission (NRC) or agreement state. Naturally occurring radioisotopes, such as potassium-40, tritium (T), and carbon-14 are routinely found in the human body from ingestion of food and water. Cosmic radiation is constantly present where exposure increases with altitude.

BACKGROUND AND THEORY OF OPERATION

The first betavoltaic battery was developed in 1953 at the RCA by Rappaport. The device yielded an efficiency of only 0.2 % and degraded rapidly due to radiation damage from the beta source, strontium-90 [2-4]. Several others continued research using ^{147}Pm but were only able to achieve <1 % efficiency [5, 6]. The most promising effort in the early history of betavoltaic developments occurred ca. 1974 through research led by Olsen at the Donald W. Douglas Laboratories [7-9]. Olsen's Betacel battery exhibited a 4 % efficiency using ^{147}Pm and silicon p n junctions. Over 285 patients received pacemakers powered by the Betacel batteries, 60 patients inside the United States. German and U. S. medical institutions were seriously considering the Betacel for wider use. The United States Atomic Energy Commission (USAEC) had authorized the licensing in the United States of a Clinical Investigation Program that allowed the implantation of 50 Betacel pacemakers per month [10]. However, strides in lithium battery development entered onto the scene and were subsequently selected for pacemakers instead [11].

Most research and development in the last 10 years has concentrated on designs using tritium; since the radiation damage is low and thus easily shielded, and relatively available. City Labs successfully produced tritium betavoltaic prototypes in 2008 (fig. 1), that are still operating. The Nano Tritium™ betavoltaic was granted a NRC General License which is approved for manufacture and sales within the United States.

A recent Recent surveys of the betavoltaic power sources show varied applications of the betavoltaics [12, 13] indicating they are a safe enabling technology for military and commercial applications;very long operating life under harsh environmental conditions. The current literature indicates better semi conductor materials such as silicon and gallium nitride and tritium and nickel-63 as best beta sources [13]. There are a few commercial companies that are developing betavoltaic cells at power ranges of micro watts. The technology is far from maturity with much room for improvement. Specific challenges exist in the loading of tritium in thin films, large aspect ratio beta sources, radiation damage in the *p-n* junction material and enhancement of energy conversion efficiency. Efforts to improve betavoltaic conversion efficiencies are currently on-going as researcher's experiment with three-dimensional device architectures, optimize semi conductor material growth techniques, and investigate utilizing tritium stored in different phases of matter.

A betavoltaic cell creates electricity similar to a photovoltaic or solar cell [14,15]. In a betavoltaic cell, electrons are produced indirectly via the kinetic energy of the beta particles interacting within the semiconductor. The basic concept of operation is shown in fig. 2. The beta particle enters the *p-n* junction and collides with atoms creating electron-hole pairs (EHP) as it slows down. A portion of the kinetic energy is lost to the lattice. A 5 keV particle creates 1000 or more EHP, and those created near the intrinsic or depletion region contribute to the generated current collected at the contacts. The number of EHP is proportional to the band gap energy of the material, the minimum energy for an electron to move to the conduction band, and the number of defects or traps where recombination occurs. The holes are accelerated to the *p*-side collector and the electrons are accelerated to the *n*-side collector. EHP created outside the depletion layer quickly recombine and provide a net current of zero. With a load connected, the electrons travel from the *n*-side, through the load and back to the *p*-side. The electrical characteristic for a single diode is shown in fig. 3. The peak power occurs at about 0.8 V and can be used in a constant current mode or constant voltage mode, depending on the application. The cells can be stacked in parallel and series.

The high energy beta or other radiation can affect or degrade the performance of the *p-n* junction. The ef-

Figure 1. City Labs nanotritiumTM betavoltaics

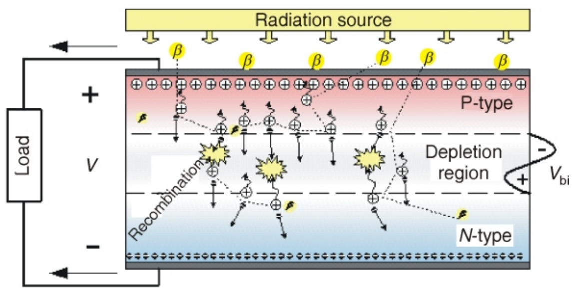

Figure 2. Overview of a betavoltaic cell

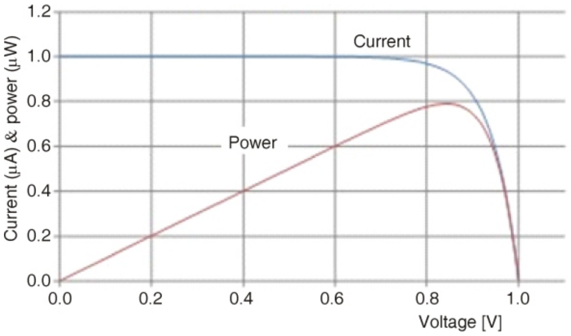

Figure 3. Typical I-V characteristics of a betavoltaic cell

fects of radiation on the performance of solar cells have been studied with the goal of developing solar cells that have greater resistance to radiation. The radiation as of neutron and gamma rays on the Si solar cells under low light conditions show reduced efficiency up to 42 % from the initial values for a single cell and up to 47 % for poly-crystalline cells [16, 17].

Combining the betavoltaic in parallel with a solid-state lithium rechargeable (secondary) battery can provide latent and burst power for many applications. In a design using a Cymbet 50 μAh lithium solid-state rechargeable battery, the operating temperature is limited to 85 °C, the maximum operating temperature of the battery. The power of the betavoltaic will be based on the burst power required and duty cycle of the sensor. Various methods of controlling the betavoltaic current to prevent overcharging the solid-state battery is being investigated. A hybrid design, shown schematically in fig. 4 will alleviate self-discharge losses at high temperatures.

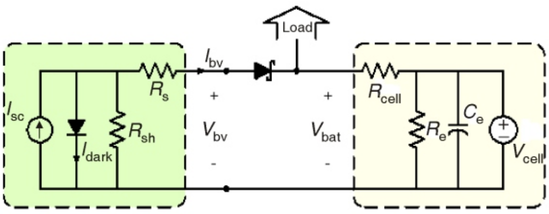

Figure 4. Hybrid betavoltaic and lithium battery

EXPERIMENTS

The I-V characteristics of each betavoltaic were measured at various temperature conditions. The setup shown in fig. 5, consists of a temperature chamber, source measurement unit and a personal computer (PC) with data acquisition software. Monitor cables are 24 gauge twisted pairs shielded to remove noise.

The temperature chamber is a Test Equity Model 107, which is programmable to operate from 132 °C down to –40 °C and does not require liquid nitrogen forcooling. Betavoltaics are tested inside the chamber. A chamber was programmed to the profile shown in fig. 6 where the temperature is cycled daily between

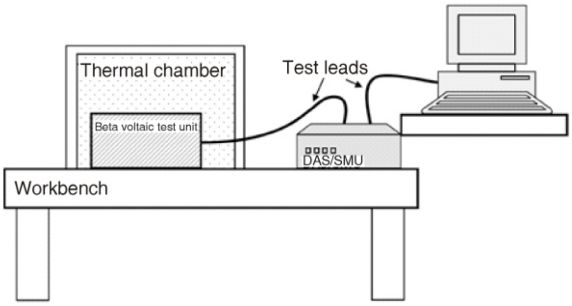

Figure 5. Betavoltaic experiment set-up

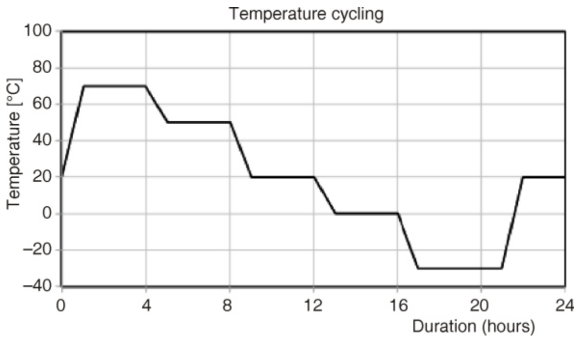

Figure 6. Temperature cycling profile for betavoltaic evaluation

80 °C, 25 °C and –40 °C. A thermocouple read temperature data and stored the readings in a separate standalone data logger installed on the PC. Ramp time between temperatures is one hour. Betavoltaic measurements are taken 30 minutes after a temperature is reached to allow for thermal equilibrium.

The Keithley 2602B source measurement unit (SMU) is used to perform current-voltage measurements (or I-V curves). Both channels are used; channel A connects to cell 1 and channel B connects to cell 2. The unit is interfaced with a PC by Ethernet. Measurements are presently executed using a Keithley TSP (Test Script Processor) Express software tool. LabView GUI is being developed to invoke the Keithley to conduct and I-V test and save data. Both channels can be operated simultaneously. Each channel can source the current and measure voltage or source voltage and measure the current. The source can either be stepped as shown below or pulsed in a positive or negative direction. Other options are sample rates, integration time and number of measurement loops. The results can be viewed, plotted and saved in the Data tab.

RESULTS

Betavoltaics were evaluated under temperature from –30 °C to 70 °C by applying a voltage and sinking the current using a Keithley 2602B source measurement unit. For individual cells, Current-voltage (I-V) curves were acquired by stepping the voltage from 1.00 V to -0.10 V in steps of 1 mV and measuring the current. Figure 7 shows I-V curves measured on Sample BV07.

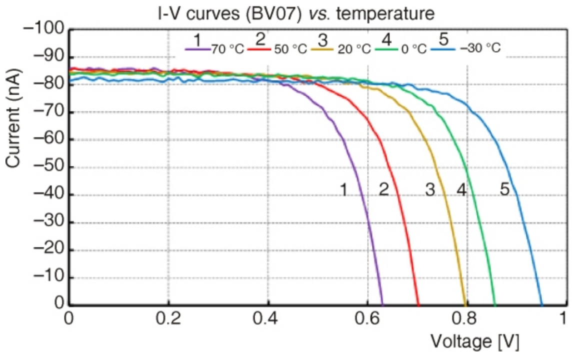

Figure 7. I-V curve4s of sample BV07 at temperatures from –30 °C to 70 °C

From cold to hot, the open-circuit voltage, V_{oc}, decreased from 0.95 V to 0.65 V while the short-circuit current (I_{sc}) increased from 82 nA to 86 nA. Because of the strong temperature dependence on voltage, the maximum power increases with decreasing temperature.

Six betavoltaic cells connected in the series were evaluated from –30 °C to 70 °C. I-V curves were acquired by stepping the voltage from 5.00 V to 0.10 V in steps of 5 mV and measuring the current. Figure 8 shows that betavoltaics can operate in series where V_{oc} and I_{sc} operate similar to individual cells. To fully charge the battery to 4.1 V in a hybrid design, seven betavoltaic cells in series are needed at 70 °C while five cells are needed at 30 °C. The lithium solid-state rechargeable battery performance evaluated under temperatures from 30 °C to 70 °C showed that the charge/discharge times increase by 20 % from the coldest temperature.A hybrid design that operates at both extremes requires control circuitry that is being developed to prevent overcharging the battery.

A plot of V_{oc} *vs*. temperature for samples BV06 and BV07 in fig. 9 indicates it decreases at a rate of 4.0 and 3.2 mV/K, respectively. The difference in the V_{oc} *vs*. temperature rate is a function of the *p-n* junction properties, which indicated the variability between lots when they were made.

The sensitivity of the current and temperature was evaluated by plotting I_{sc} *vs*. temperature. Figure 10 shows that the current decreases with temperature

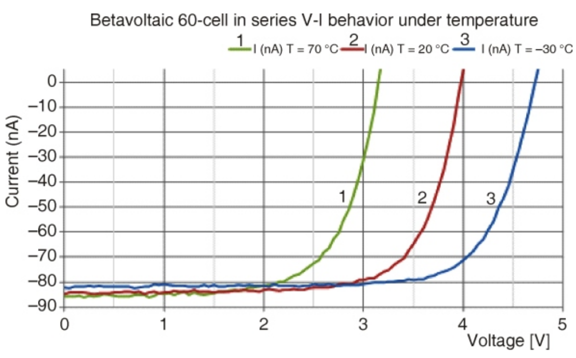

Figure 8. I-V curves of six samples (BV07-BV11) connected in series at temperatures from –30 °C to 70 °C

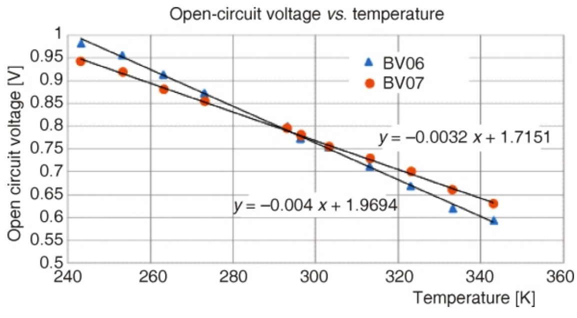

Figure 9. V_{oc} temperature for samples BV06 and BV07

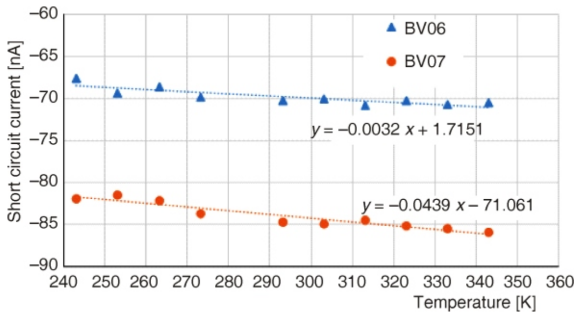

Figure 10. I_{sc} vs. temperature for samples BV06 and BV07

at a rate of 0.025 and 0.044 nA/K for Samples BV06 and BV07, respectively. The large difference between the current is due to the passivation quality of the *p-n* junction surface.

CONCLUSIONS

Betavoltaic power sources are a safe enabling technology for military and commercial applications that require decadal time periods under harsh environmental conditions. Hybrid designs where betavoltaics trickle charge a solid-state battery or capacitor offer potential uses in sensors and surveillance devices. The fact that betavoltaics deliver more power as temperature decreases makes them a suitable replacement for cold temperature applications where batteries fail. Though performance degrades at a higher temperature, it is not permanent and returns to its same performance as the temperature lowers. The technology is far from maturity with much room for improvement. Understanding the effects of temperature and other external forces on performance will assist designers in using the technology and research in identifying critical areas that can be improved.

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AUTHORS' CONTRIBUTIONS

Experiments were planned and the paper was written by T. Adams and S. T. Revankar. Experiments were conducted by T. Adams and D. Cheu. The test betavolatics were supplied by P. Cabauy and B. Elkind. All authors analyzed and discussed the results.

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ПЕРФОРМАНСЕ БЕТАНАПОНСКИХ БАТЕРИЈА ПРИ ЕКСТРЕМНИМ ТЕМПЕРАТУРАМА

Дуговечност сензора и преносивих уређаја значајно је ограничена температуром, хемијском нестабилношћу и цурењем електролита код конвенционалних електрохемијских батерија. Бетанапонске батерије, које раде слично фотонапонским, могу поуздано служити у широком температурном опсегу без трајног слабљења. Иако ово није новина, започета 50-их година прошлог века са врхунцем 70-их година, истраживање у овој области било је минимално и узгредно, све до скорашњег напретка у електроници ултраниских снага и достигнућа примене ниских снага. Технологија је убрзано сазревала, подстичући истраживања и развој у повећању извора бета зрачења и ефикасности полупроводника. Овај рад представља савремен приказ технологије бетанапонских батерија, резултата процене утицаја температуре на комерцијално доступне лиценциране бетанапонске батерије, развоја хибридног система за латентну и снагу праска, моделовања и технике симулације са резултатима, текућег и даљег правца развоја и истраживања. Својства бетанапонских батерија успешно су предствљена у широком опсегу температура од –30 °C до 70 °C, коришћењем струје кратког споја и напона празног хода – ради поређења електричних перформанси. Резултати показују да услед раста сопствене концентрације носилаца наелектрисања полупроводника, напон празног хода и максимална снага опадају са порастом температуре.

Кључне речи: бетанапонска батерија, снага радиоактивног извора, прикупљање енергије, хибридна батерија, полупроводничка батерија, бета емитер, p-n спој, латентна снага, ниска снага, моделовање