Nuclear Engineering and Design xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Nuclear Engineering and Design

journal homepage: www.elsevier.com/locate/nucengdes

Experiments and modeling on effects of temperature on electrical performance of a betavoltaic

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ARTICLE INFO

Article history:
Received 20 October 2016
Received in revised form 22 May 2017
Accepted 19 June 2017
Available online xxxx

Keywords:
Betavoltaic
Nuclear battery
Temperature effects
Electrical performance

ABSTRACT

Betavoltaic cells' electrical performance was assessed by measuring current-voltage properties (I-V curves) and determining short-circuit current and open-circuit voltage. These properties were obtained on three betavoltaics under temperature cycles between −30 °C and 70 °C. Results indicated that the open-circuit voltage decreased as temperature increased and changes in short-circuit current were negligible, but betavoltaic cells were operational in the tested temperature range. In addition, a semi-empirical method to predict betavoltaic performance was developed. An I-V curve of the betavoltaic cell is taken at a reference temperature where the open-circuit voltage and short-circuit current is derived. Variations in the semiconductor's band gap energy are used to predict the open-circuit voltage at various temperatures within 10% error and was compared with City Labs' NanoTritium™ batteries.

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1. Introduction

Chemical batteries are the most commonly used sources of power for lightweight and portable application. However, their lifetimes are often shortened requiring replacement every few years and performance is limited to a temperature range. Nuclear batteries, which utilize a radioisotope to generate power, are an alternative power source that are impervious to these issues. Nuclear batteries have extensive lifespans, are resistant to temperature changes and can function at extreme temperatures. Betavoltaics are an example of a nuclear battery that uses a beta-emitting source, such as tritium, nickel-63 or promethium-147, and operates on the same principles as photovoltaics or solar cells.

Betavoltaic cells were first invented in 1953 by coupling an alloy of strontium-90 and yttrium-90 to a silicon semiconductor junction. However, this device had an efficiency of 0.2% and the semiconductor degraded quickly due to radiation damage from the high energy beta particles emitted from the source (Jenny et al., 1956). In the early 1970s, Olsen's group developed the first betavoltaic power source called Betacel and was licensed for use in cardiac pacemakers (Olsen et al., 2012). Betacel consisted of alternating layers of silicon semiconductors and Prometheium-147 in the form of Pm_2O_3 and had an efficiency of 4%, produced 400 μW and lasted up to 10 years (Ko and Hynecek, 1974). However, the use of Promethium-147 resulted in the presence of Promethium-146, a gamma-ray emitting radioisotope, which required heavy shielding for use. Due to the limited availability of Promethium-147, as well as the rise of lithium-ion batteries which was cheaper alternative, led to the current, extensive use of lithium-ion batteries in cardiac pacemakers (Olsen et al., 2012).

Even though there have been multiple demonstrations of betavoltaics with various combinations of radioisotopes and semiconductor configurations, the evaluations on behavior of betavoltaic under multiple temperatures is limited. Chandrashekhar performed the first temperature evaluation of a 4H SiC temperature transducer from a range of 24 °C to 86 °C (Chandrashekhar et al., 2006). Wang performed a temperature evaluation on two ^{63}Ni sourced, Si p-n junction and expanded the temperature range to be between −40 °C and 60°C (Wang et al., 2010). Investigation into betavoltaic temperature evaluation expanded further by Nejad, when a ^{63}Ni sourced, Si p-n junction was modelled to predict temperature using the temperature dependent V_{oc} using MCNP code but a physical betavoltaic cell was not tested (Ghasemi Nejad et al., 2014). A group at Lockheed Martin examined the power and energy density of betavoltaic cells by multiple manufacturers including City Labs Inc. (Adams and Revankar, 2014).

In this work, an experimental study the effects of operating temperature on the electrical performance of commercially made betavoltaic cells from City Labs Inc., the NanoTritium™ battery, consisting of a tritium source and a Gallium Arsenide (GaAs) p-n junction. The effects of temperature on NanoTritium™ cells' I-V characteristics were studied. The paper discusses how the Shockley

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http://dx.doi.org/10.1016/j.nucengdes.2017.06.028
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diode model can be used as a method of predicting the betavoltaic's sensitivity to temperature by creating a semi-empirical model and comparing it to experimental results.

2. Experimental methods

Three City Labs' NanoTritium™ betavoltaic cells were used for this experiment since they have an NRC (National Regulatory Commission) general license which allows for use outside of an NRC approved facility. The NanoTritium™ cells utilize a tritium source stored in a solid matrix which irradiates a planar GaAs p-n junction. The only difference between each cell used in this paper was the tritium's activity which can be approximated based on their initial measurements. However, additional information such as the N and P doping concentrations, series and shunt resistances of the p-n junction are not known due to manufacturer propriety. Known information for each betavoltaic cell used in this experiment are listed in Table 1, where the activity of BV06 is significantly higher than the activity in BV07 and BV08. Important material properties are proprietary to the manufacturer and were not provided.

Even though the operational temperature range for the NanoTritium™ cells are listed from −40 °C to 80 °C in City Labs' specification sheet, measurements were carried out in a temperature chambered cycled from −30 °C to 70 °C and back down to −30 °C in steps of 10 °C. Each temperature step lasted for an hour, where the temperature ramps up or down by 10 °C for the first 10 min and soaks for the remaining 50 min. After 45 min into the temperature soak, I-V curves were measured from −0.1 V to 1.0 V by a Keithley 2602B source measurement unit (SMU).

Table 1
Individual betavoltaic cell properties.

Property	BV06	BV07	BV08
Model	P100a	P100a	P100a
Serial number	102012002	920140001	90140010
Manufacture date	11/1/2011		
Original activity [mCi]	310	154	154
Activity during testing [mCi]	234.3	116.4	116.4

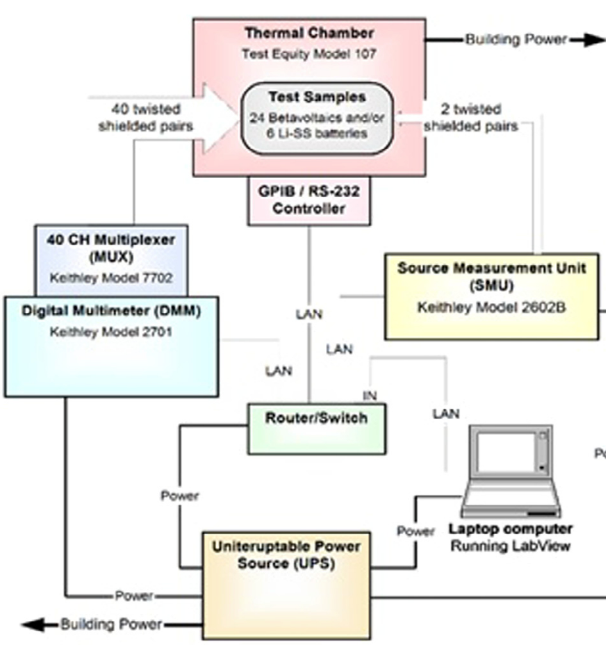

Fig. 1. Experimental setup.

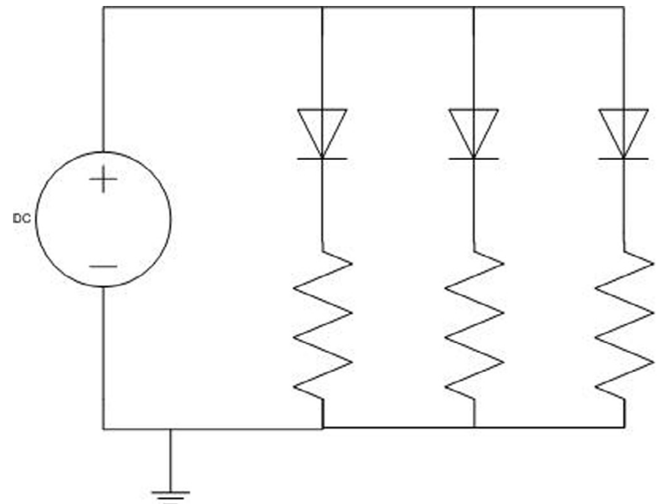

Fig. 2. Betavoltaic evaluation circuit diagram.

An overview of the experiment set up is shown in Fig. 1. In the temperature chamber, three betavoltaic cells were connected in parallel. The source measurement unit, a Keithley Model 2602B, applied a voltage across the parallel connected betavoltaics and a Keithley Model 2701 measured the current across each 1 kΩ resistor in series with a betavoltaic cell as shown in Fig. 2. From the I-V curves, the open-circuit voltage V_{oc}, which is the voltage where no current flows through the external circuit and the maximum voltage a solar cell can deliver, and the short-circuit current I_{sc} which is the maximum output current and no voltage is delivered by the solar cell, of each cell were found, and were plotted versus temperature.

3. Experimental results

The I-V curves measured from the betavoltaics at each temperature are shown in Fig. 3 through Fig. 5 for cells BV06, BV07 and BV08, respectively. As temperature increased, the I-V curves began to move closer towards the origin as V_{oc} began to decrease as shown in Fig. 6 and values shown in Table 2. The change in V_{oc} was higher in BV06 compared to the other cells due to its higher activity. In addition, the V_{oc} gathered had a maximum variance of 0.01 V at each temperature which shows no hysteresis effects from temperature after repeated cycling for two weeks.

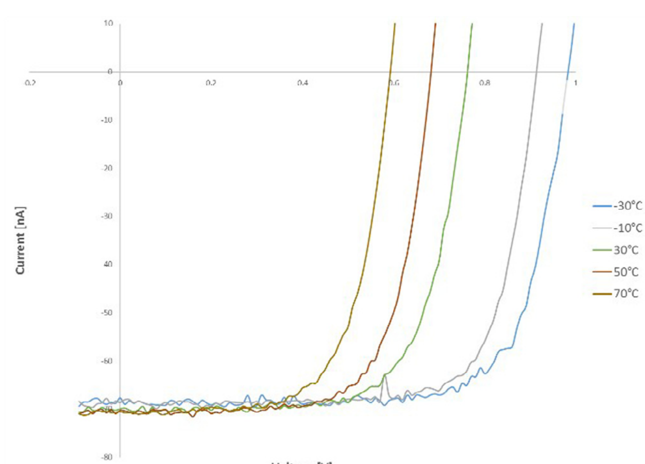

Fig. 3. I-V curves from BV06 at various temperatures*.

Please cite this article in press as: Cheu, D.S., et al. Experiments and modeling on effects of temperature on electrical performance of a betavoltaic. Nucl. Eng. Des. (2017), http://dx.doi.org/10.1016/j.nucengdes.2017.06.028

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