ENCAPSULATED RADIOISOTOPE FOR EFFICIENCY IMPROVEMENT OF NUCLEAR MICROBATTERY

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Abstract: This paper describes an improved betavoltaic microbattery based on a new loading method of the radioisotope material. The radioactive material sulfur (^{35}S) was blended with a semiconductor material (selenium) and volumetrically encapsulated within the harvesting semiconductor device. It produced more efficient energy conversion than traditional approaches by utilizing a maximum available energy from the isotropically radiating source without extra shielding structures. The prototype devices with encapsulated radioisotope was fabricated and tested at room temperature. The maximum power of 76.53nW was obtained from 10.89mCi of ^{35}S. The overall efficiency of the prototype device was about 2.42%.

Keywords: Radioisotope, betavoltaic, encapsulation, and microbattery

INTRODUCTION

Nowadays, there are enormously growing needs of small and light power sources with a long life time for many sensors in hardly accessible locations. Lots of former research attempts have been made to achieve lighter weight and higher energy density for such power sources [1, 2]. Due to the high energy density, long life time, and durability in extreme environments, radioisotope power sources have been considered for the long-term reliable micropower sources [3].

In general, radioisotope based batteries convert the emission of ionizing radioisotope sources into electrical energy. The conversion technique can be categorized to two main types: 1. direction conversion, in which radioactivity is converted directly into electrical energy such as betavoltaic and fission electric cells; and 2. indirect conversions, in which radioactivity is converted into intermediate energy (thermal or photon energy) and then converted to electrical energy. For the micropower sources, betavoltaic conversion is much more preferred than alphavoltaic due to the fact the alpha emitters contain extremely a high energy dose, which can quickly damage the micro device. An early attempt on betavoltaic conversion was introduced by Rappaport in 1953 [4]. The concept of bombarding the silicon-alloy junction with a high radiation dose of Sr^{90}-Y^{90} resulted in an overall efficiency of only about 0.4%. Later in mid-60s-70s, various compact betavoltaics were extensively developed and tested by Olsen at Donald W Douglas laboratories for space and medical applications. One of them with overall efficiency of about 1.7% (Betacel model 400 – relatively large and heavy) had been used for pacemaker [5].

Most betavoltaics consist of two major parts: 1) a beta emitting radioactive source; and 2) a harvesting semiconductor device (rectifying PN junction diode). Electron-hole pairs (EHPs) are created in the semiconductor by the ionization of beta radiation. At the depletion region, the EHPs separated by the built-in electric field at the rectifying junction create potential drops. The typical structures of betavoltaic are illustrated in Figure 1. The typical betavoltaic cells have externally located radioactive sources on the front side of the cell, where the rectify junction is located and converts the beta radiation to electrical energy. Since the radiation intensity gets reduced dramatically while it is travel, there is an inevitable energy loss. In 2005, W. Sun introduced 10% of gain improvement (0.22% with tritium ^{3}H) from the increased active area of the rectify junction by using porous structure.

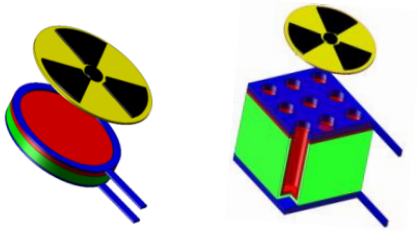

Fig. 1: 3D view of the conventional betavoltaics (a) planar structure (b) porous structure.

In addition, the self-absorption issue and high dose beta particles can limit the efficiency of betavoltaic microbatteries. Very strong energetic beta particle may damage the rectify junction easily, and shorten the life time of the device. In this paper, we introduce a new method to improve the overall efficiency of the betavoltaic microbattery through full consideration of various losses.

DESIGN FOR IMPROVING EFFICIENCY

To design a device with higher efficiency, we have studied about the losses of radioactive energy for the betavoltaics. The total loss (L_{Total}) can be represented as

$$L_{Total} = L_d + L_a + L_m + L_i$$

where L_d , L_a , L_m , and L_i are directional loss, absorption loss, median loss and interaction loss, respectively. The details are as follows:

a) Directional loss (L_d)

The energy loss due to the radiation direction is regarded as a directional loss. We have simply estimated how much energy can be utilized for the energy conversion from the radioisotope source because the unused energy is not a trivial loss to overlook for the efficiency improvement. As can be seen in Figure 2, a noticeable amount of energy (more than a left half) from the radiation source hasn't been considered to be utilized in many conventional approaches. The radioactive martial emits beta particles with a continuous energy spectrum in all direction. But only less a half of the total energy from the radioactive source is being converted while the other half is simply wasted. In addition, the top surface of the harvesting semiconductor device allows only a small portion of the half to pass through the small windows in the metal layers. As a result, the effective zone of a space charge region (stimulated by radiation) is very limited by the size of the opening windows.

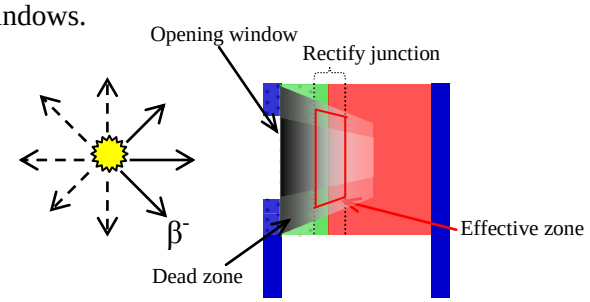

Fig. 2: The schematics illustrating the losses mechanism of emitted beta partials

b) Absorption loss (L_a)

If a thick layer of radioactive material is used as a beta source, self-absorption will take place before the beta radiation can escape from its martial. Generally, radioactive materials with low beta energy are affected seriously by the self-absorption such as ^{63}Ni and ^{3}H. When the specific activity per unit area (mCi/cm^2) of radioactive is increased by increasing the mass per unit area (mg/cm^2) of the radioactive material, the self-absorption per unit area will also be increased as well. For example, in case of nickel ^{63}Ni, the loss from self-absorption can be increased up to 20% of the actual activity [6].

c) Median loss (L_m)

The radiation loss between the radioisotope source and betavoltaic cell is regarded as a median loss. A fraction of the radiated beta particles is ionized and gives up some energy before reaching the harvesting semiconductor device. The amount of loss depends on various physical properties of the specific material in between. The path of electron is not linear due to the scattering from nuclei. The high energy electron tends to have a straight and long path unlike the low energy electron. For example, when the radiation source (^{63}Ni) is placed far away (about 2mm) from the conventional betavoltaic surface, the cell exhibits the 11 times lower overall efficiency [6]. Thus, it is clear that the closer the radioactive source is placed, the more energy is collected.

d) Interaction loss (L_i)

The interaction loss between beta particles and the harvesting semiconductor device is considered to be a significant loss. From the beta radiation, the ionization loss is proportional to the atomic number (z), and logarithmic of energy. Consequently, majority of the losses occurs at the electrode metal (high Z metal), and the dead zone in the semiconductor. In the isotropic distribution of the beta particles, loss from the backscattering is claimed to be approximately 30% [7].

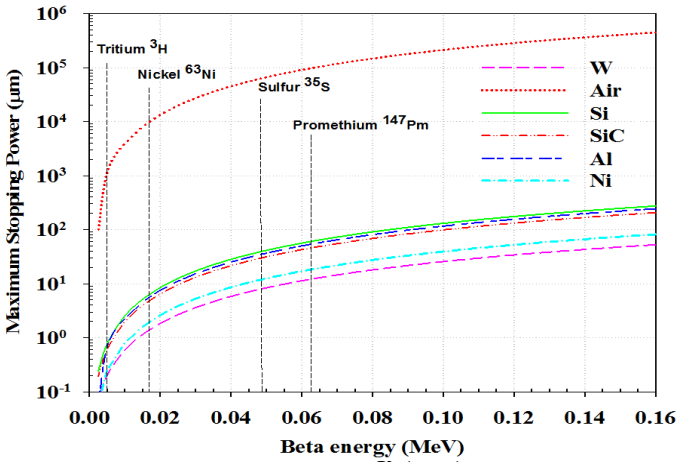

Fig. 3: Maximum stopping power of beta particles in different materials with the average beta energy from variety of radioactive (^{3}H, ^{63}Ni, ^{35}S, and ^{147}Pm).

The continuum slow down approximation range theory can be used to predict the range of emitted beta particles. The relationship between maximum stopping power of beta particles and different materials is shown in Figure 3. The average beta

energy data of several radioactive materials are also shown. For example, the average β^- energy (17.6 keV) of ^{63}Ni can be stopped in less than 8μm of a semiconductor layer and in less than 2μm of a metal layer. The maximum stopping distance is predominated by the density, atomic weight, and mean exciting potential of the material.

In addition to the various loss factors described above, the bulkiness of the radiation shielding structures critically affect the size of the device. Thus, most conventional radioisotope micropower sources suffer from inefficient device structure and energy conversion

NEW APPROACH

Unlike the conventional methods, our approach utilizes the idea of encapsulating the radioisotope source within a semiconductor cell as illustrated in Figure 4. The radioactive material is mixed with a semiconductor. A metal-semiconductor Schottky diode is implemented instead of the silicon-based PN junction device.

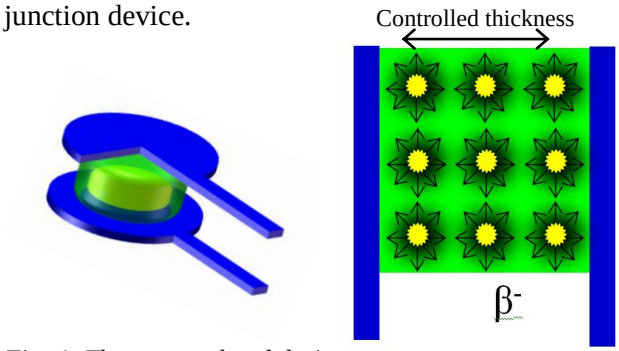

Fig. 4: The encapsulated design for betavoltaic.

With the encapsulation method, L_d can be minimized. Beta particles travel in random directions within the semiconductor and all the energy can contribute to generate EHPs. In addition, the new approach is not limited by the opening window in the metal electrode of the conventional devices.

Also L_a and L_m can be completely eliminated since the radioactive and semiconductor is very close to each other. For the selection of radioactive source, high beta spectrum energy and high specific activity are two main parameters to be considered. L_i can be reduced by adjusting the thickness of semiconductor. The thickness of semiconductor has to be thin enough so that the beta radiation can cover whole volume of the semiconductor in the device.

Another advantage is that the encapsulation method can provide a secure self-shielding and eliminate the need of extra shielding structures. It allows a remarkably smaller device than the conventional ones. Lastly, it is very cost effective because the harvesting semiconductor device doesn't contain costly silicon-based materials.

EXPERIMENT AND DISCUSSION

Sulfur ^{35}S was chosen as a radioactive source. It has a pure beta emitter with average beta energy of 49 keV and a half-life of 87.3 days. It can be enriched with a high specific activity up 42,707 Ci/g compare to tritium (^{3}H) 72.97 Ci/g and ^{63}Ni 56.56 Ci/g. The maximum range of the beta particle is less than 26cm in air and 250 microns in plastic, which is ideal for shielding and safety handling [8].

After radioactive sulfur ^{35}S and selenium was mixed and confined in the reservoir (20μm deep), the device was enclosed by the cover substrate (glass) by using thermocompression bonding technique. To avoid interference of electromagnetic waves, the device was tested in a glove box under a controlled environment. 10.89 millicurie of radioactive sulfur 35 was used in this experiment. The *IV* characteristics were measured with a Keithley 2400 picoammeter/voltage source at room temperature (27 ^{o}C). Figure 5 shows the dark current data of the device. A short circuit current (I_{SC}) of 752nA and the open circuit voltage (V_{OC}) of 864mV were observed.

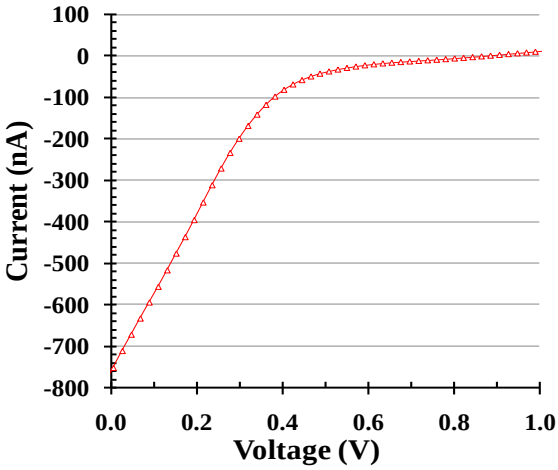

Fig. 5: The I-V characteristic of encapsulated device at room temperature

Figure 6 shows the output power against bias voltage. A maximum power of 76.53nW was obtained at 193mV. The overall efficiency conversion of encapsulated betavoltaic with ^{35}S (402MBq) is 2.42%. It is much higher than every one of the conventional radioisotope microbatteries as shown in Table 1, which compares and summarizes many betavoltaic technologies including a couple of commercially available old models. Most of them have a disadvantage of bulky shielding structures resulting in low power density. To compare the power density,

Table 1: Comparison of various betavoltaic

Reference	[5]	[9]	[10]	[11]	Our device
Device	Betacel (model 50)	Schottky betavoltaic	Promethium-147 atomic battery	BetaBatt inc	Encapsulated betavoltaic
Structure	Silicon P/N	Silicon/gold Schottky	Silicon P/N	Porous silicon P/N	Selenium/aluminum Schottky
Source	Pm147 (12ci)	Pm147 (26.4ci)	Pm147 (6.8ci)	Tritium ^{3}H (0.11ci)	Sulfur ^{35}S (10.89mci)
Energy max	224 keV	224 keV	224 keV	18.6keV	167 keV
Power	50μw	8.7 μw	9 μw	8.3nW	76.53nW
Overall efficiency	1.0%	0.09%	0.77%	0.22%	2.42%
Total scale device	H=1.02cm D=1.52cm	H=1.27cm D=2.54cm	n/a	H=1.27cm D=2.54cm	H=0.2cm W=2.54cm L_{bottom}=3.81cm L_{cover}=2.54cm
Radiation dose	at surface ~50mrem/hr	at surface 9 mrem/hr	n/a	n/a	less than 1mrem/hr
Total Volume(cm^3)	1.85 cm^3	6.31cm^3	Less than 32.7 cm^3	Less than 41.45 cm^3	1.93 cm^3
Normalized power with 10ci (μW)	41.58	3.28	13.25	0.75	70.27
Estimated Power density with 10ci (μW/ cm^3)	22.48	0.52	0.40	0.18	36.41

each device's output power is normalized to 10Ci of its radioactivity. Our device shows roughly twice larger power density than that of the conventional device (Betacel model 50). Thus, we believe that higher total power density of nearly 36.41μW/cm^3 can be achieved in this encapsulated design with the proper radioisotope material selection.

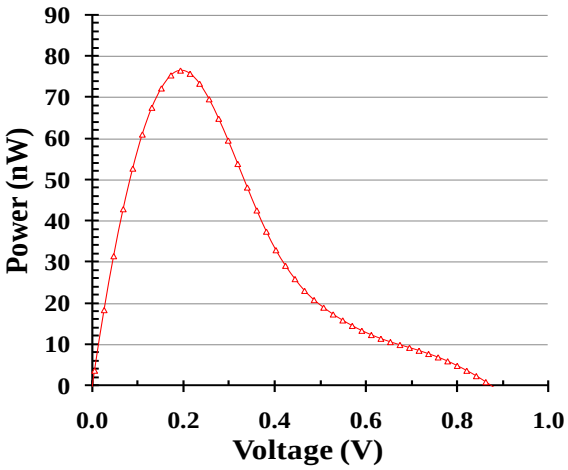

Fig. 6: Output power against the bias voltage

CONCLUSION

We have successfully demonstrated many advantages of our new design of betavoltaic with an improved overall efficiency (2.42%). The radioactive material was encapsulated inside of the semiconductor and the prototype device produced 76.53nW from radioactive ^{35}S (402MBq) at room temperature. Also, an open-circuit voltage (752mV) and short-circuit current (864nA) were observed. Future work is required for the device with smaller size and higher efficiency.

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